U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-284 614

A Mathematical Model of Electrostatic Precipitation. (Revision 1): Volume I Modeling and Programming

Southern Research Inst, Birmingham, Ala

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, N C

Jun 78

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-78-111a
June 1978

Research and Development

PB 284 614

A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume I. Modeling and Programming

Interagency Energy/Environment R&D Program Report

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

REVIEW NOTICE

This report has been reviewed by the participating Federal Agencies, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-78-111a	2.	3. RECIPIENT'S ACCESSION NO. PB284614
4. TITLE AND SUBTITLE A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume I. Modeling and Programming		5. REPORT DATE June 1978
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Jack R. McDonald		8. PERFORMING ORGANIZATION REPORT NO. 3540-6 SORI-EAS-78-101
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southern Research Institute 2000 Ninth Avenue, South Birmingham, Alabama 35205		10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADL-027
		11. CONTRACT/GRANT NO. 68-02-2114
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Revision; 6/75-2/78
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Leslie E. Sparks, Mail Drop 61, 919/541-2925. EPA-650/2-75-037 was the initial report.

16. ABSTRACT The report briefly describes the fundamental mechanisms and limiting factors involved in the electrostatic precipitation process. It discusses theories and procedures used in the computer model to describe the physical mechanisms, and generally describes the major operations performed in the computer program. It lists the entire computer program and defines all variables used in the program. Major improvements to the fundamental basis of the model include: the capability of generating theoretical voltage-current characteristics for wire-plate geometries, a new method for describing the effects of rapping reentrainment, and a new procedure for predicting the effects of particles on the electrical conditions. The computer has been made more user oriented by making the input data less cumbersome, by making the output data more complete, by making modifications which save computer time, and by providing for the construction of log-normal particle size distributions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Dust	Stationary Sources	11G
Electrostatic Precipitation	Particulates	13H
Mathematical Models		12A
Computer Programming		09B

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 332
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE PC A15/MF A01

EPA Form 2220-1 (9-73)

EPA-600/7-78-111a
June 1978

A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume I. Modeling and Programming

by

Jack R. McDonald

Southern Research Institute
2000 Ninth Avenue, South
Birmingham, Alabama 35205

Contract No. 68-02-2114
ROAP No. 21ADL-027
Program Element No. 1AB012

EPA Project Officer: Leslie E. Sparks

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

ia

DISCLAIMER

This report was prepared as an account of work sponsored by the United States Government. The report has been reviewed by the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. Neither the United States nor the U.S. Environmental Protection Agency, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, process or computer program disclosed, or represents that its use would not infringe privately owned rights.

ABSTRACT

The objectives of this research program were to upgrade the fundamental basis of the existing model of electrostatic precipitation developed under the sponsorship of the Environmental Protection Agency, to make the computer program which performs the calculations required by the model more user oriented, and to fully document those subroutines in the computer program that perform fundamental calculations or utilize numerical techniques.

In this report, the fundamental mechanisms and limiting factors involved in the electrostatic precipitation process are described briefly. The theories and procedures used in the model to describe the physical mechanisms are discussed. A general description of the major operations which are performed in the computer program is given. A listing of the entire computer program and the definitions of all the variables used in the program are provided.

Major improvements to the fundamental basis of the model include the capability of generating theoretical voltage-current characteristics for wire-plate geometries, a new method for describing the effects of rapping reentrainment, and a new procedure for predicting the effects of particles on the electrical conditions.

The computer program has been made more user oriented by making the input data less cumbersome, by making the output data more complete, by making modifications which save computer time, and by providing for the construction of log-normal particle size distributions.

Those subroutines in the computer program that perform fundamental calculations or utilize numerical techniques are described in sufficient detail to provide an understanding of their content and usage. A detailed flow chart is provided for each of these subroutines. Input and output variables are described and any limitations on these variables are noted.

A complete description of the input data to the computer program is provided so that the program can be utilized. Modifications which can be made to the computer program to adapt it to different computers and to extend its capabilities are discussed.

This report was submitted in partial fulfillment of Task VI of Contract No. 68-02-2114 by Southern Research Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers a contract period from June 30, 1975 to February 28, 1978, and work was completed as of February 15, 1978.

CONTENTS

Disclaimer.... ii
Abstract.... iii
Figures.... vii
Tables.... x
Nomenclature.... xi
Metric Conversion Factors.... xx

1. Introduction.... 1
2. Conclusions.... 4
3. Recommendations.... 5
4. Fundamental Steps in the Electrostatic Precipitation Process.... 7
    - Creation of an electric field and corona current.... 7
    - Particle charging.... 9
    - Particle collection.... 14
    - Removal of collected material.... 16
5. Limiting Factors Affecting Precipitator Performance.... 17
    - Allowable voltage and current density.... 17
    - Methods for predicting fly ash electrical resistivity.... 19
    - Nonideal effects.... 19
6. Description of the Mathematical Model.... 22
    - Ideal calculation of particle collection efficiency.... 22
    - Methods for estimating nonideal effects.... 29
    - Empirical corrections to no-rap migration velocities.... 36
    - Estimation procedure for calculating particle collection efficiencies.... 39
7. Computer Programing of the Mathematical Model.... 42
    - Description of the computer program.... 42
    - Descriptions of the subroutines.... 45
8. Description of Input Data.... 141
    - General description.... 141
    - Construction of the basic data set.... 141
    - Construction of shortened data sets.... 160
9. Machine-Dependent Aspects of the Computer Program.... 165

References.... 170

Appendices

A. Development of New Procedure for Determining Space Charge Effects.. 174
B. Definitions of Variables Used in the Main Program and Subroutines.. 190
C. Complete Listing of the Computer Program.............. 262

FIGURES

Number		Page
1a	Region near small-radius electrode..................	8
b	Electric field configuration for wire-plate geometry.......................................	8
2	Electric field configuration during field charging..	11
3a	Electric field configuration and ion distribution for particle charging with no applied field.........	12
b	Electric field configuration and ion distribution for particle charging in an applied electric field after saturation charge is reached............	12
4	Measured rapping emissions versus calculated particulate removal by last electrical section. These curves are a result of work sponsored by the Electric Power Research Institute..........................	34
5	Apparent rapping puff size distribution for six full-scale precipitators. These data are a result of work sponsored by the Electric Power Research Institute..	37
6	Average rapping puff size distribution for six full-scale precipitators. These data are a result of work sponsored by the Electric Power Research Institute..	38
7	Empirical correction factors for the "no-rap" migration velocities calculated from the mathematical model. This work was sponsored by the Electric Power Research Institute..................	40
8	Simplified flow chart for the entire program........	46-49
9	Flow chart for subroutine SPCHG1....................	50
10	Flow chart for subroutine SPCHG2....................	53-54
11	Flow chart for subroutine CMAN......................	58-59

12 Nomenclature used in the numerical analysis of the electrical conditions in wire-plate precipitators... 61

13 Partial grid showing nomenclature used in the numerical analysis of the electrical conditions..... 62

14 Flow chart for subroutine EFLD1...................... 67-69

15 Flow chart for subroutine EFLD2...................... 73-80

16 Flow chart for subroutine CHARGN..................... 85

17 Flow chart for statement function RATE.............. 88-92

18 Flow chart for subroutine ARCCOS..................... 95

19 Flow chart for subroutine ZERO....................... 97

20 Flow chart for subroutine CHGSUM..................... 99-101

21 Flow chart for subroutine ADJUST..................... 106-117

22 Flow chart for subroutine WADJST..................... 123

23 Flow chart for subroutine LNDIST..................... 127-129

24 Flow chart for subroutine QTFE....................... 131

25 Flow chart for subroutine LNFIT...................... 135

26 Flow chart for subroutine CFIT....................... 139

27 Flow chart for the input data logic................. 163-164

28 Nomenclature used in the procedure which determines particulate space charge effects.................... 176

29 Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 33 kV.................................. 181

30 Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 35 kV.................................. 182

31 Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 40 kV.................................. 183

32 Theoretical voltage-current curves for a specific collection area of 19.7 $m^2/(m^3/sec)$................ 185

33 Theoretical voltage-current curves for a specific collection area of 59.1 $m^2/(m^3/sec)$................ 186

34 Theoretical voltage-current curves for a specific collection area of 98.4 $m^2/(m^3/sec)$................ 187

35 Comparison of theoretical voltage-current curves for different specific collection areas............ 188

36 Comparison of model predictions using the different space charge schemes with field test data from a full-scale precipitator. Model predictions are for unadjusted, no-rap efficiencies where $\sigma_g = 0.25$ and $S = 0$.......................... 189

TABLES

Number		Page
1	Particle Sizes and Correction Factors for No-Rap Migration Velocities Tabulated in Subroutine WADJST..	121
2	Reduced Effective Negative Ion Mobilities for Various Gas Compositions..........................	150
3	Values of Viscosity for Air at Various Temperatures and Water Contents................................	158
4	Core Requirements for Various Segments of the Computer Program...................................	166

NOMENCLATURE

w_p	Migration velocity near the collection electrode of a particle of radius a, m/sec
q	Charge on a particle, coul
E_p	Electric field near the collection electrode, V/m
a	Particle radius, m
μ	Gas viscosity, kg/m-sec
C	Cunningham correction factor (or slip correction factor)
λ	Mean free path of gas molecules, m
A'	Quantity defined by $[1.257 + 0.4 \exp(-1.1\, a/\lambda)]$
η_m	Collection fraction for a monodisperse aerosol
A_p	Collection electrode area, m^2
Q	Gas volume flow rate, m^3/sec
V_L	Voltage drop across the collected particulate layer, V
j	Current density in the collected particulate layer, A/cm^2
ρ'	Resistivity of the collected particulate layer, ohm-cm
t	Thickness of the collected particulate layer, cm
E_L	Average electric field in the collected particulate layer, V/cm
$\eta_{i,j}$	Ideal collection fraction for the i-th particle size in the j-th increment of length of the precipitator
$w_{i,j}$	Migration velocity of the i-th particle size in the j-th increment of length of the precipitator, m/sec
A_j	Collection electrode area in the j-th increment of length of the precipitator, m^2

η_i	Ideal collection fraction for a given particle size over the entire length of the precipitator
$N_{i,j}$	Number of particles of the i-th particle size per cubic meter of gas entering the j-th increment, $\#/m^3$
η	Ideal overall mass collection efficiency for the entire polydisperse aerosol, %
P_i	Percentage by mass of the i-th particle size in the inlet size distribution, %
V	Electric potential at a given point in a precipitator, V
ρ	Total space charge density at a given point in the gas in a precipitator, coul/m^3
b_e	Effective charge carrier mobility, m^2/V-sec
y	Coordinate parallel to the gas flow from wire-to-wire, m
x	Coordinate perpendicular to the gas flow from wire-to-plate, m
ε_0	Permittivity of free space, coul/N-m^2
J_p	Average current density at the collection plate, A/m^2
ρ_{pi}	Space charge densities for various points on the collection plate, coul/m^3
E_{pi}	Electric field strengths for various points on the collection plate, V/m
N	Number of grid points in the direction of gas flow in the electric field calculations
q	Instantaneous particle charge, coul
q_s	Saturation charge due to field charging, coul
θ	Azimuthal angle in a spherical coordinate system with origin at the center of the particle, radians
θ_0	Maximum azimuthal angle for which electric field lines enter a charged particle, radians
N_0	Free ion density, $\#/m^3$
e	Electronic charge, coul

E_0	Average electric field between the discharge electrodes, V/m
b	Ion mobility, m^2/V-sec
$\tilde{v}$	Mean thermal speed of ions, m/sec
k	Boltzmann's constant, J/°K
T	Absolute temperature of the gas, °K
t	Time, sec
K	Dielectric constant of the particle
r_0	Radial distance along θ at which the radial component of the total electric field is zero, m
q_D	Charge predicted from classical diffusion charging theory, coul
q_F	Charge predicted from classical field charging theory, coul
t_i	Initial time for charging under a fixed set of conditions, sec
t_f	Final time for charging under a fixed set of conditions, sec
q_i	Charge on the particle at time t_i, coul
b'	Effective ion mobility, m^2/V-sec
j_t	Total current density at the collection plate due to ions and particles, A/m^2
j_p	Particulate current density at the collection plate, A/m^2
w	Migration velocity for a given particle diameter which is calculated from fundamental principles and applies only to a given length increment as used in the model, cm/sec
w_e	Effective migration velocity for a given particle diameter which is calculated from fundamental principles and applies to the entire length of the precipitator, cm/sec
w_e'	Apparent effective migration velocity for a given particle diameter which is obtained by making an empirical correction (or corrections) to w_e, cm/sec

w_{pr}	precipitation rate parameter which provides a measure of how well the entire mass which enters the precipitator will be collected, cm/sec
F_i	Particle diameter-dependent correction factors for nonuniform gas velocity distribution
σ_g	Normalized standard deviation of the gas velocity distribution
P_{N_S}	Penetration of a given particle size from the last baffled section which is corrected for gas sneakage
S	Fractional amount of gas sneakage per baffled section
N_s	Number of baffled sections
B_i	Particle diameter-dependent correction factors for gas sneakage and/or nonrapping reentrainment
$w_{e,i}$	Effective migration velocity for the i-th particle diameter, cm/sec
$w'_{e,i}$	Apparent effective migration velocity for the i-th particle diameter, cm/sec
P_{N_R}	Penetration of a given particle size which is corrected for nonrapping reentrainment
R	Fraction of collected material reentrained per section
N_R	Number of sections over which reentrainment is assumed to occur
η'/section	Total mass collection fraction per linear electrical section under normal operating conditions
η_0	Overall mass collection fraction determined from mass train measurements under normal operating conditions
X'	Quantity which is equal to $-\ln(1-\eta_0)$
N_E	Number of electrical sections in series
X	Calculated mass removal by the last electrical section, mg/DSCM
y_1	Measured rapping emissions from cold-side precipitators, mg/DSCM
y_2	Measured rapping emissions from hot-side precipitators, mg/DSCM

d_{50} (MMD)	Mass median diameter of a log-normal particle size distribution, μm
σ_p	Geometric standard deviation of a log-normal particle size distribution
V_w	Applied voltage, V
S_x	Wire-to-plate spacing, m
S_y	One half wire-to-wire spacing, m
r_w	Radius of corona wire, m
a_x	Increment size in the x-direction used in calculating electrical conditions, m
a_y	Increment size in the y-direction used in calculating electrical conditions, m
E_x	x-component of the electric field, V/m
E_y	y-component of the electric field, V/m
V_0	Electric potential at an arbitrary point in a numerical grid, V
ρ_0	Space charge density at an arbitrary point in a numerical grid, coul/m^3
α	Parameter in the equation for ρ_0, coul/m^3
β	Parameter in the equation for ρ_0, coul^2/m^6
α_{AB}	Values of α along a line from wire to wire, coul/m^3
α_{BC}	Values of α along a line midway between wires from the plane of the wires to the plate, coul/m^3
α_{AD}	Values of α along a line from the wire to the plate, coul/m^3
α_{CD}	Values of α along the plate, coul/m^3
β_{AB}	Values of β along a line from wire to wire, coul^2/m^6
β_{BC}	Values of β along a line midway between wires from the plane of the wires to the plate, coul^2/m^6
β_{AD}	Values of β along a line from the wire to the plate, coul^2/m^6

β_{CD}	Values of β along the plate, $coul^2/m^6$
ρ_s	Space charge density at the outer boundary of the ionized corona sheath, $coul/m^3$
b_s	Effective charge carrier mobility at the outer boundary of the ionized corona sheath, m^2/V-sec
f	Roughness factor of the corona wires
δ	Relative density of the gas
ρ_w	Space charge density near the corona wire, $coul/m^3$
r_s	Radius of the ionized corona sheath, m
E_s	Electric field at the outer boundary of the ionized corona sheath, V/m
E_c	Corona starting electric field, V/m
$\frac{dy}{dx}$	Derivative of the variable y with respect to the variable x where x and y represent unspecified quantities
$f(x,y)$	Arbitrary function of x and y
k_n	Weighting factors in a Runge-Kutta integration scheme ($n = 1,2,3,4$)
Δy	Increment for advancing the dependent variable in the Runge-Kutta integration scheme
h	Increment size for the independent variable in the Runge-Kutta, Simpson's Rule, and trapezoidal rule integration schemes
$x_n(x_i)$	Values of the independent variable in the Runge-Kutta and Simpson's Rule integration schemes
$y_n(y_i)$	Values of the dependent variable in the Runge-Kutta, Simpson's Rule, and trapezoidal rule integration schemes
n	Number of charges on a particle
c_1	Coefficient of X in the cubic equation (53)
c_2	Factor in the constant term in the cubic equation (53)
$f_{L-N}(z)$	Log-normal distribution function

d	Particle diameter, μm
z	Independent variable for the log-normal distribution
$\bar{z}$	Mean value of z
σ_z	Standard deviation of z
M	Total mass contained in a log-normal particle size distribution, kg/m^3
F_i	Mass fractions for the different size bands in a log-normal particle size distribution
S_i	Cumulative mass fractions in a log-normal particle size distribution
Z_i	Cumulative integrals obtained in a trapezoidal rule integration
$S(X)$	Cumulative fraction up to a given particle size in a log-normal distribution
t	Transformation variable for a log-normal distribution
t'	Lower limit for the integration of a Gaussian integral over the variable t
$Q(t)$	Cumulative fraction greater than a given particle size
ϕ	Variable in terms of which t can be expressed
a_0, a_1, a_2	Coefficients in an approximate expression for t'
b_1, b_2, b_3	Coefficients in an approximate expression for t'
z'	Natural logarithm of a known or measured particle diameter corresponding to a known or measured cumulative mass fraction
$\bar{z}'$	Mean value of z'
A	Quantity which is equal to $-\bar{z}'/\sigma_z$
B	Quantity which is equal to $1/\sigma_z$
m	Number of data points in a least squares fit to a straight line
Δ	Parameter obtained in a least squares fit to a straight line

r	Linear-correlation coefficient
$\bar{J}_\ell$	Average current density in the l-th subincremental length of a given length increment, A/m^2
$\bar{E}_\ell$	Average electric field in the l-th subincremental length of a given length increment, V/m
$\bar{\rho}_\ell$	Average total particulate charge density in the l-th subincremental length of a given length increment, $coul/m^3$
$\bar{\rho}_{i,\ell}$	Average charge density for the i-th particle size at the end of the l-th subincremental length of a given length increment, $coul/m^3$
$X_{i,\ell}$	Number of particles per unit volume of gas of the i-th particle size entering the l-th subincremental length of a given length increment, $\#/m^3$
$q_{i,\ell}$	Charge on the i-th particle size at the end of the l-th subincremental length of a given length increment, coul
$\bar{b}_\ell$	Weighted particulate mobility due to all particles in the l-th subincremental length of a given length increment, $m^2/V\text{-}sec$
C_i	Cunningham correction factor (or slip correction factor) for the i-th particle size
a_i	Radius of the i-th particle size, m
X_ℓ	Total number of particles per unit volume of gas entering the l-th subincremental length of a given length increment, $\#/m^3$
$\bar{\rho}'_\ell$	Average ionic charge density with a particulate mass loading in the l-th subincremental length of a given length increment, $coul/m^3$
b'	Molecular ion "effective mobility", $m^2/V\text{-}sec$
$\bar{\rho}''_\ell$	Average ionic charge density without a particulate mass loading in the l-th subincremental length of a given length increment, $coul/m^3$
$\Delta\bar{\rho}_\ell$	Average charge density shifted from molecular ions to particles in the l-th subincremental length of a given length increment, $coul/m^3$

b_ℓ^e	Effective mobility due to both ions and particles in the l-th subincremental length of a given length increment, m^2/V-sec
$w_{i,\ell}$	Migration velocity of the i-th particle size in the l-th subincremental length of a given length increment, m/sec
$\bar{E}_\ell^p$	Average electric field at the collection plate in the l-th subincremental length of a given length increment, V/m
$\eta_{i,\ell}$	Ideal collection fraction for the i-th particle size in the l-th subincremental length of a given length increment
b^e	Average effective mobility for ions and particles over a length equal to one wire-to-wire spacing, m^2/V-sec
$\bar{J}_w$	Average current density near the wire without particles, A/m^2
$\bar{J}_w'$	Average current density near the wire with particles, A/m^2
A_p'	Collection plate area receiving current from a single wire, m^2
A_w	Surface area of a single wire, m^2
$\bar{J}_p$	Average current density at the collection plate for an area receiving current without particles from a single wire, A/m^2
$\bar{J}_p'$	Average current density at the collection plate for an area receiving current with particles from a single wire, A/m^2

METRIC CONVERSION FACTORS

To Convert From	To	Multiply by
grams/ft^3	kg/m^3	0.00229
ft	m	0.3048
ft^2	m^2	0.0929
in	m	0.0254
ft^3/min	m^3/sec	0.000472
ft/sec	m/sec	0.3048
°F	°K	$(°F+459) \times \frac{1}{1.8}$

SECTION 1

INTRODUCTION

The electrostatic precipitation process involves several complicated and interrelated physical mechanisms: the creation of a nonuniform electric field and ionic current in a corona discharge; the ionic and electronic charging of particles moving in combined electro- and hydro-dynamic fields; and the turbulent transport of charged particles to a collection surface. The removal of the collected particulate layer from the collection surface presents a serious problem in many practical applications since the removal procedures introduce collected material back into the gas stream and cause a reduction in collection efficiency. Other practical considerations which reduce the collection efficiency are nonuniform gas velocity distribution, bypassage of the electrified regions by particle-laden gas, and particle reentrainment during periods when no attempt is being made to remove the collected material.

In recent years, increasing emphasis has been placed on developing theoretical relationships which accurately describe the individual physical mechanisms involved in the precipitation process and on incorporating these relationships into a complete mathematical model for electrostatic precipitation. From a practical standpoint, a reliable theoretical model for electrostatic precipitation would offer several valuable applications:

(1) precipitator design could be easily and completely performed by calculation from fundamental principles;

(2) a theoretical model could be used in conjunction with a pilot-plant study in order to design a full-scale precipitator;

(3) precipitator bids submitted by various manufacturers could be evaluated by a purchaser with respect to meeting the design efficiency and the costs necessary to obtain the design efficiency;

(4) the optimum operating efficiency of an existing precipitator could be established and the capability to meet particulate emissions standards could be ascertained; and

(5) an existing precipitator performing below its optimum efficiency could be analyzed with respect to the different operating variables in a procedure to troubleshoot and diagnose problem areas.

In addition to its many applications, a mathematical model can be a valuable tool for analyzing precipitator performance due to its cost and time savings capability. The approach is cost effective because it (1) allows for the analysis and projection of precipitator operation based upon a limited amount of data (extensive field testing is not necessary), (2) can predict trends caused by changing certain precipitator parameters and thus, in many cases, can prevent costly modifications to a precipitator which will not significantly improve the performance, (3) can be used as a tool in sizing precipitators and prevent excessive costs due to undersizing or significant oversizing, and (4) can be used to obtain large amounts of information without extensive use of manpower but, instead, with reasonable use of a computer.

The approach is time effective because (1) large amounts of information can be generated quickly, (2) it does not necessarily depend on time-consuming field tests which involve travel, extensive analysis, and plant and precipitator shut-downs, (3) it can prevent losses in time due to unnecessary or insufficient modifications to a precipitator, and (4) it can prevent losses in time due to the construction of an undersized precipitator.

In the present work, a revised model of electrostatic precipitation developed by Southern Research Institute under the sponsorship of the Environmental Protection Agency (Industrial Environmental Research Laboratory, Research Triangle Park) is discussed. The first version of the model is described in the publication entitled "A Mathematical Model of Electrostatic Precipitation."[1] The present report is separated into two volumes. Volume 1 contains a description of the physical mechanisms involved in the electrostatic precipitation process, the physical and mathematical formulation of the model, and a documentation of a computer program which implements the model. Volume 2 is a user's manual which describes how to use the model for various purposes. This volume includes a description of input and output data and relates these quantities to the various applications of the model.

The version of the model described in the present text has the following features:

(1) it predicts collection efficiency as a function of particle diameter, electrical operating conditions, and gas properties;

(2) it can calculate clean-plate, clean-air voltage-current characteristics for wire-plate geometries;

(3) it determines particle charging by unipolar ions as a function of particle diameter, electrical conditions, and residence time;

(4) it can estimate the effects of particles on the electrical conditions under the assumption that effects due to the particulate layer can be ignored;

(5) it accounts for electrical sectionalization;

(6) it predicts particle capture at the collection electrode based on the assumptions of completely-random, turbulent flow, uniform gas velocity, and particle migration velocities which are small compared to the gas velocity;

(7) it employs empirical correction factors which adjust the particle migration velocities obtained without rapping losses;

(8) it accounts for the nonideal effects of nonuniform gas velocity distribution, gas bypassage of electrified regions, and particle reentrainment from causes other than rapping by using empirical correction factors to scale down the ideally-calculated particle migration velocities; and

(9) it accounts for rapping reentrainment by using empirical relationships for the quantity and size distribution of the reentrained mass.

In its present form, the model has the capability of predicting trends caused by changes in specific collection area, applied voltage, current density, mass loading, and particle size distribution. Comparisions of the predictions of the model with laboratory-scale precipitators[2] and full-scale precipitators collecting fly ash from coal-fired boilers[1,3,4] indicate that the model can be used successfully to predict precipitator performance.

SECTION 2

CONCLUSIONS

The version of the mathematical model of electrostatic precipitation presented in this report offers greater predictive capabilities and is more user oriented than the previous version. Greater predictive capabilities are provided by allowing for the calculation of theoretical voltage-current characteristics for wire-plate geometries, by use of a new method for determining the effects of rapping reentrainment that is directly related to full-scale precipitators, by incorporation of a new method for estimating the effects of particles on the electrical conditions, and by the use of experimentally-determined, empirical correction factors for individual particle migration velocities that results in increased agreement between the theory and field test data. The computer program which performs the calculations required by the model is more user oriented than the previous program due to modifications that make the input data less cumbersome, make the output data more complete and useful, result in savings of computer time, and allow for the construction of log-normal particle size distributions. Detailed documentation of those subroutines which perform fundamental calculations or utilize numerical techniques should provide a firm basis for understanding their content and usage.

SECTION 3

RECOMMENDATIONS

Although the mathematical model of electrostatic precipitation presented in this report represents a significant improvement over the previous version, more work still needs to be performed in order to improve the fundamental basis and user oriented aspects of the model.

With respect to the fundamental basis of the model, it is recommended that the following research be pursued:

1. Theoretical and experimental studies of the effects of particles on the electrical conditions should be continued in order to better describe the effect on the electric field distribution.

2. Theoretical and experimental studies of electrical breakdown mechanisms in the collected particulate layer should be given greater emphasis in an attempt to acquire the capability of theoretical prediction of when electrical breakdown will ensue for a given resistivity.

3. Since the model underpredicts the collection efficiencies for fine particles without the use of empirical correction factors, theoretical and experimental studies should be continued in order to remove the empiricism. These studies should include a reevaluation of the theories presently used in the model and an examination of those effects which are presently neglected such as particle charging near corona wires and phenomena due to the gas flow field.

4. The mathematical model should be restructured to take into account time-dependent effects. The effects due to the growth of the particulate layer and the rapping schedule should be included as a function of time. Although the empirical procedure employed in the present version of the model represents a useful interim technique for estimating the effects due to rapping reentrainment in precipitators, it does not describe the temporal and dynamic aspects of the rapping process. The inclusion of time-dependent effects is necessary in order to optimize the electrical operating conditions and the rapping schedule and intensity.

The above research is needed in order to make the model independent of empiricism and of the experience and judgment of the user.

With respect to the user oriented aspects of the model, it is recommended that the following work be performed:

1. Alternative numerical techniques need to be investigated and implemented in order to make the computer program run significantly faster.

2. Procedures which edit the input data should be implemented.

3. Documentation of the computer program needs to be included in abbreviated form in the computer card deck.

The above work is needed in order to continue the transition in which the model is transformed from a research tool to a production tool.

SECTION 4

FUNDAMENTAL STEPS IN THE ELECTROSTATIC PRECIPITATION PROCESS

CREATION OF AN ELECTRIC FIELD AND CORONA CURRENT

The first step in the precipitation process is the creation of an electric field and corona current. This is accomplished by applying a large potential difference between a small-radius electrode and a much larger radius electrode, where the two electrodes are separated by a region of space containing an insulating gas. For industrial applications, a large negative potential is applied at the small-radius electrode and the large-radius electrode is grounded.

At any applied voltage, an electric field exists in the interelectrode space. For applied voltages less than a value referred to as the "corona starting voltage", a purely electrostatic field is present. At applied voltages above the corona starting voltage, the electric field in the vicinity of the small-radius electrode is large enough to produce ionization by electron impact. Between collisions with neutral molecules, free electrons are accelerated to high velocities and, upon collision with a neutral molecule, their energies are sufficiently high to cause an electron to be separated from a neutral molecule. Then, as the increased number of electrons moves out from the vicinity of the small-radius electrode, further collisions between electrons and neutral molecules occur. In a limited high electric field region near the small-radius electrode, each collision between an electron and a neutral molecule has a certain probability of forming a positive molecular ion and another electron, and an electron avalanche is established. The positive ions migrate to the small-radius electrode and the electrons migrate into the lower electric field regions toward the large-radius electrode. These electrons quickly lose much of their energy and, when one of them collides with a neutral electro-negative molecule, there is a probability that attachment will occur and a negative ion will be formed. Thus, negative ions, along with any electrons which do not attach to a neutral molecule, migrate under the influence of the electric field to the large-radius electrode and provide the current necessary for the precipitation process.

Figure 1a is a schematic diagram showing the region very near the small-radius electrode where the current-carrying negative

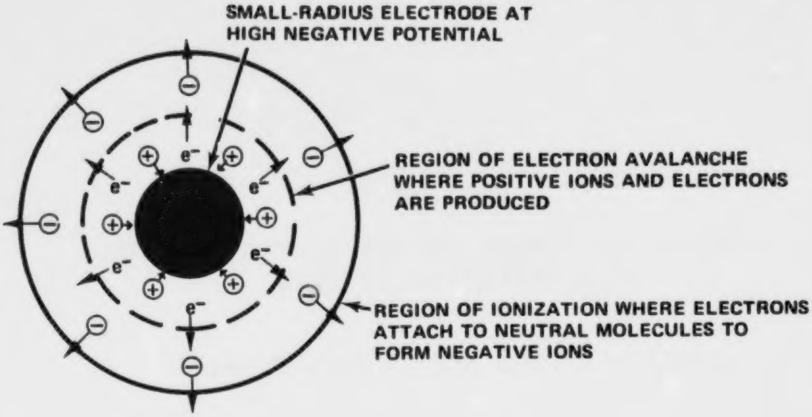

SMALL-RADIUS ELECTRODE AT HIGH NEGATIVE POTENTIAL
REGION OF ELECTRON AVALANCHE WHERE POSITIVE IONS AND ELECTRONS ARE PRODUCED
REGION OF IONIZATION WHERE ELECTRONS ATTACH TO NEUTRAL MOLECULES TO FORM NEGATIVE IONS
e⁻

Figure 1a. Region near small-radius electrode.

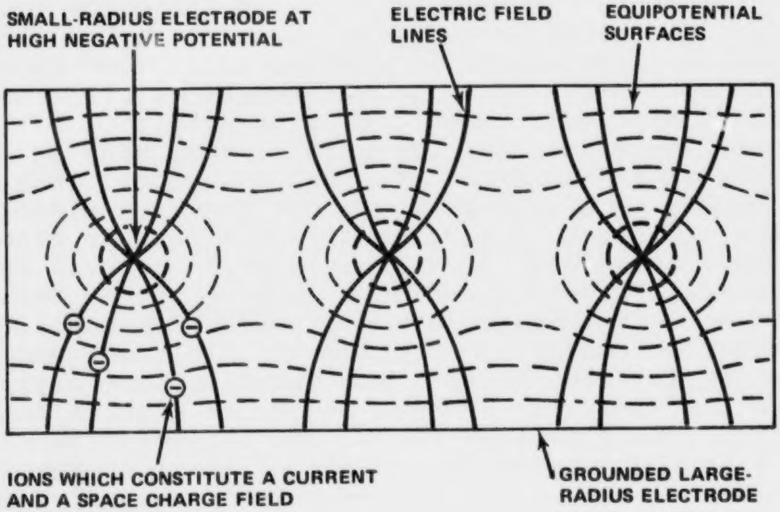

SMALL-RADIUS ELECTRODE AT HIGH NEGATIVE POTENTIAL
ELECTRIC FIELD LINES
EQUIPOTENTIAL SURFACES
IONS WHICH CONSTITUTE A CURRENT AND A SPACE CHARGE FIELD
GROUNDED LARGE-RADIUS ELECTRODE

Figure 1b. Electric field configuration for wire-plate geometry.

ions are formed. As these negative ions migrate to the large-radius electrode, they constitute a steady-state charge distribution in the interelectrode space which is referred to as an "ionic space charge". This "ionic space charge" establishes an electric field which adds to the electrostatic field to give the total electric field. As the applied voltage is increased, more ionizing sequences result and the "ionic space charge" increases. This leads to a higher average electric field and current density in the interelectrode space.

Figure 1b gives a qualitative representation of the electric field distribution and equipotential surfaces in a wire-plate geometry which is most commonly used. Although the electric field is very nonuniform near the wire, it becomes essentially uniform near the collection plates. The current density is very nonuniform throughout the interelectrode space and is maximum along a line from the wire to the plate.

In order to maximize the collection efficiency obtainable from the electrostatic precipitation process, the highest possible values of applied voltage and current density should be employed. In practice, the highest useful values of applied voltage and current density are limited by either electrical breakdown of the gas throughout the interelectrode space or of the gas in the collected particulate layer. High values of applied voltage and current density are desirable because of their beneficial effect on particle charging and particle transport to the collection electrode. In general, the voltage-current characteristics of a precipitator depend on the geometry of the electrodes, the gas composition, temperature, and pressure, the particulate mass loading and size distribution, and the resistivity of the collected particulate layer. Thus, maximum values of voltage and current can vary widely from one precipitator to another and from one application to another.

PARTICLE CHARGING

Once an electric field and current density are established, particle charging can take place. Particle charging is essential to the precipitation process because the electrical force which causes a particle to migrate toward the collection electrode is directly proportional to the charge on the particle. The most significant factors influencing particle charging are particle diameter, applied electric field, current density, and exposure time.

The particle charging process can be attributed mainly to two physical mechanisms, field charging and thermal charging.[5,6,7] These two mechanisms are discussed below.

(1) At any instant in time and location in space near a particle, the total electric field is the sum of the electric field

due to the charge on the particle and the applied electric field. In the field charging mechanism, molecular ions are visualized as drifting along electric field lines. Those ions moving toward the particle along electric field lines which intersect the particle surface impinge upon the particle surface and place charge on the particle.

Figure 2 depicts the field charging mechanism during the time it is effective in charging a particle. In this mechanism, only a limited portion of the particle surface $(0 \leq \theta < \frac{\pi}{2})$ can suffer an impact with an ion and collisions of ions with other portions of the particle surface are neglected. Field charging takes place very rapidly and terminates when sufficient charge (the saturation charge) is accumulated to repel additional ions. Figure 3b depicts the electric field configuration once the particle has attained the saturation charge. In this case, the electric field lines circumvent the particle and the ions move along them around the particle.

Theories based on the mechanism of field charging agree reasonably well with experiments whenever particle diameters exceed about 0.5 μm and the applied electric field is moderate to high. In these theories, the amount of charge accumulated by a particle depends on the particle diameter, applied electric field, ion density, exposure time, ion mobility, and dielectric constant of the particle.

(2) The thermal charging mechanism depends on collisions between particles and ions which have random motion due to their thermal kinetic energy. In this mechanism, the particle charging rate is determined by the probability of collisions between a particle and ions. If a supply of ions is available, particle charging occurs even in the absence of an applied electric field. Although the charging rate becomes negligible after a long period of time, it never has a zero value as is the case with the field charging mechanism. Charging by this mechanism takes place over the entire surface of the particle and requires a relatively long time to produce a limiting value of charge.

Figure 3a depicts the thermal charging process in the absence of an applied electric field. In this case, the ion distribution is uniform around the surface of the particle and each element of surface area has an equal probability of experiencing an ion collision. Thermal charging theories which neglect the effect of the applied electric field adequately describe the charging rate over a fairly broad range of particle sizes where the applied electric field is low or equal to zero. In addition, they work well for particles less than 0.2 μm in diameter regardless of the magnitude of the applied electric field.

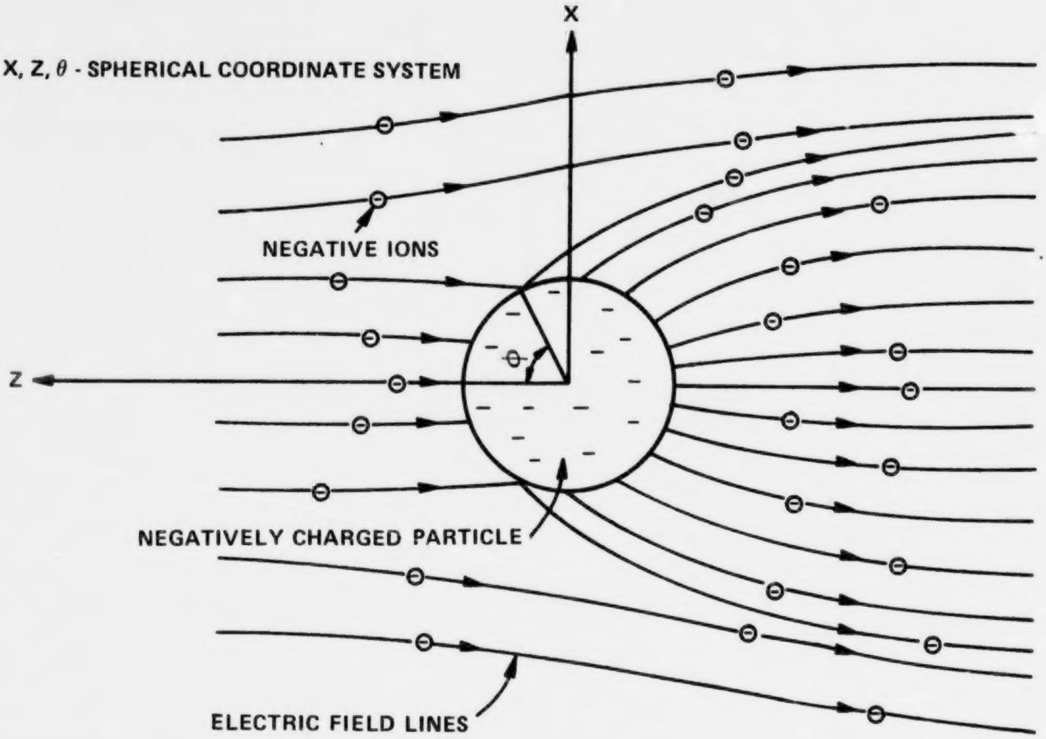

X
X, Z, θ - SPHERICAL COORDINATE SYSTEM
NEGATIVE IONS
Z
NEGATIVELY CHARGED PARTICLE
ELECTRIC FIELD LINES

Figure 2. Electric field configuration during field charging

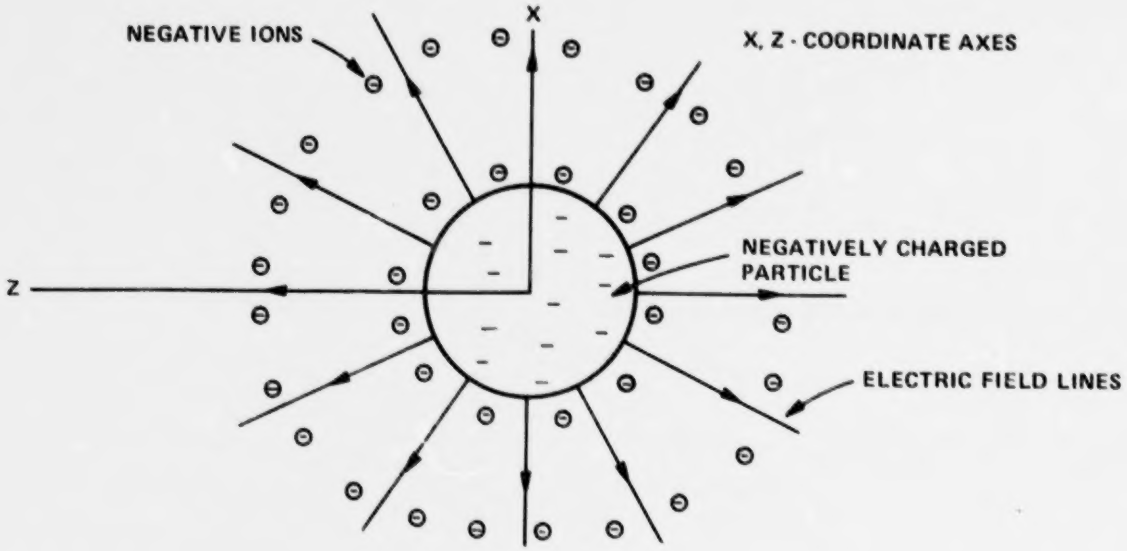

NEGATIVE IONS
X
X, Z - COORDINATE AXES
NEGATIVELY CHARGED PARTICLE
Z
ELECTRIC FIELD LINES

Figure 3a. Electric field configuration and ion distribution for particle charging with no applied field.

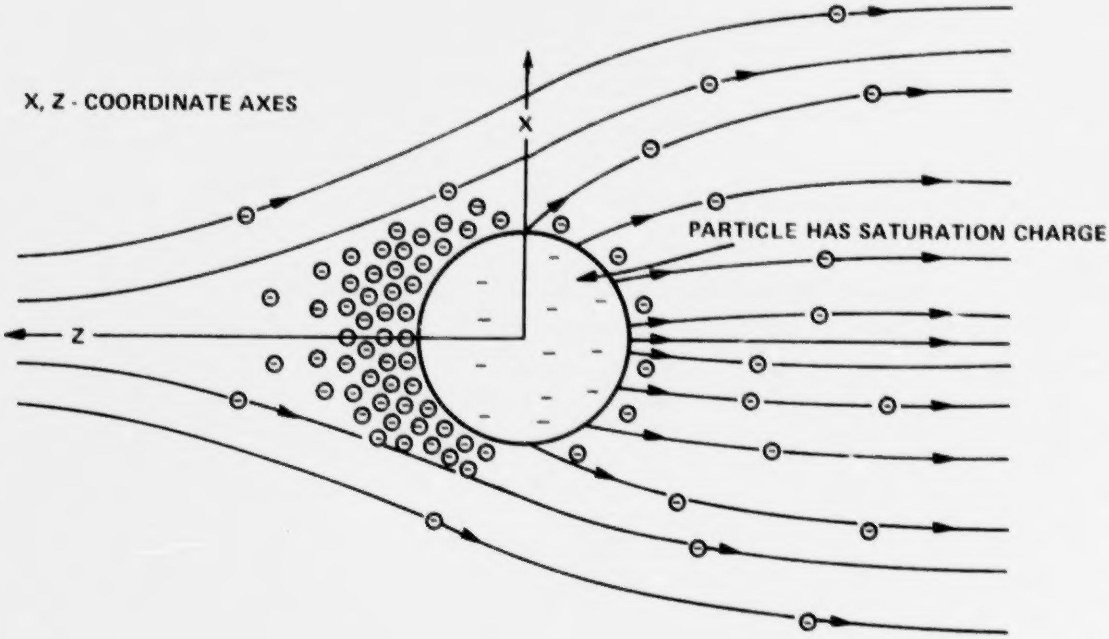

X, Z - COORDINATE AXES
X
PARTICLE HAS SATURATION CHARGE
Z

Figure 3b. Electric field configuration and ion distribution for particle charging in an applied field after saturation charge is reached.

Figure 3b depicts the thermal charging process in the presence of an applied electric field after the particle has attained the saturation charge determined from field charging theory. The effect of the applied electric field is to cause a large increase in ion concentration on one side of the particle while causing only a relatively small decrease on the other side. Although the ion concentration near the surface of the particle becomes very nonuniform, the net effect is to increase the average ion concentration, the probability of collisions between ions and the particle, and the particle charging rate.

In thermal charging theories, the amount of charge accumulated by a particle depends on the particle diameter, ion density, mean thermal velocity of the ions, absolute temperature of the gas, particle dielectric constant, residence time, and the applied electric field. The effect of the applied electric field on the thermal charging process must be taken into account for fine particles having diameters between 0.1 and 2.0 μm. Depending most importantly on the applied electric field and to a lesser extent on certain other variables, particles in this size range can acquire values of charge which are 2-3 times larger than that predicted from either the field or the thermal charging theories. For these particles, neither field nor thermal charging predominates and both mechanisms must be taken into account simultaneously.

In most cases, particle charging has a noticeable effect on the electrical conditions in a precipitator. The introduction of a significant number of fine particles or a heavy concentration of large particles into an electrostatic precipitator significantly influences the voltage-current characteristic. Qualitatively, the effect is seen by an increased voltage for a given current compared to the particle-free situation. As the particles acquire charge, they must carry part of the current but they are much less mobile than the ions. This results in a lower "effective mobility" for the charge carriers and, in order to obtain a given particle-free current, higher voltages must be applied to increase the drift velocities of the charge carriers and the ion densities.

The charged particles, which move very slowly, establish a "particulate space charge" in the interelectrode space. The distribution of the "particulate space charge" results in an electric field distribution which adds to those due to the electrostatic field and the ionic field to give the total electric field distribution. It is desirable to determine the space charge resulting from particles because of its influence on the electric field distribution, especially near the collection plate where, for the same current, the electric field is raised above the particle-free situation. In addition, the "particulate space charge" is a function of position along the length of the precipitator since particle charging and collection are a function of length.

PARTICLE COLLECTION

As the particle-laden gas moves through a precipitator, each charged particle has a component of velocity directed towards the collection electrode. This component of velocity is called the electrical drift velocity, or migration velocity, and results from the electrical and viscous drag forces acting upon a suspended charged particle. For particle sizes of practical interest, the time required for a particle to achieve a steady state value of migration velocity is negligible and, near the collection electrode, the magnitude of this quantity is given by[8]

$$w_p = \frac{qE_pC}{6\pi a\mu} \quad , \qquad (1)$$

where w_p = migration velocity near the collection electrode of a particle of radius a (m/sec),

q = charge on particle (coul),

E_p = electric field near the collection electrode (volt/m),

a = particle radius (m),

μ = gas viscosity (kg/m-sec),

C = Cunningham correction factor, or slip correction factor[9] = $(1 + A'\lambda/a)$,

where $A' = 1.257 + 0.400 \exp(-1.10\ a/\lambda)$, and

λ = mean free path of gas molecules (m).

In industrial precipitators, laminar flow never occurs and the effect of turbulent gas flow must be considered. The turbulence is due to the complex motion of the gas itself, electric wind effects of the corona, and transfer of momentum to the gas by the movement of the particles. Average gas flow velocities in most cases of practical interest are between 0.6 and 2.0 m/sec. Due to eddy formation, electric wind, and other possible effects, the instantaneous velocity of a small volume of gas surrounding a particle may reach peak values which are much higher than the average gas velocity. In contrast, migration velocities for particles smaller than 0.6 μm in diameter are usually less than 0.3 m/sec. Therefore, the motion of these smaller particles tends to be dominated by the turbulent motion of the gas stream. Under these conditions, the paths taken by the particles are random and the determination of the collection efficiency of a given particle becomes, in effect, the problem of determining the probability that a particle will enter a laminar boundary zone adjacent to the collection electrode in which capture is assured.

Using probability concepts and the statistical nature of the large number of particles in a precipitator, White[10] derived an expression for the collection efficiency in the form

$$\eta_m = 1 - \exp(-A_p w_p / Q) \quad , \tag{2}$$

where η_m = collection fraction for a monodisperse aerosol,

A_p = collection area (m^2),

w_p = migration velocity near the collection electrode of the particles in the monodisperse aerosol (m/sec), and

Q = gas volume flow rate (m^3/sec).

The simplifying assumptions on which the derivation of equation (2) is based are:

(1) The gas is flowing in a turbulent pattern at a constant, mean forward-velocity.

(2) Turbulence is small scale (eddies are small compared to the dimensions of the duct), fully developed, and completely random.

(3) The particle migration velocity near the collecting surface is constant for all particles and is small compared with the average gas velocity.

(4) There is an absence of disturbing effects, such as particle reentrainment, back corona, particle agglomeration, or uneven corona.

Experimental data[11] under conditions which are consistent with the above assumptions demonstrate that equation (2) adequately describes the collection of monodisperse aerosols in an electrostatic precipitator under certain idealized conditions.

In industrial precipitators, the above assumptions are never completely satisfied but they can be approached closely. With proper design, the ratio of the standard deviation of the gas velocity distribution to the average gas velocity can be made to be 0.25 or less so that an essentially uniform, mean forward-velocity would exist. Although turbulence is not generally a completely random process, a theoretical determination of the degree of correlation between successive states of flow and between adjacent regions of the flow pattern is a difficult problem and simple descriptive equations do not presently exist for typical precipitator geometries. At the present, for purposes of modeling, it appears practical and plausible to assume that the turbulence is highly random. For particles larger than 10 μm diameter, the turbulence does not dominate the motion of these particles due to their relatively high migration velocities. Under these conditions, equation (2) would be expected to underpredict collection efficiencies. The practical effect in modeling precipitator performance will be slight, however, since even equation (2) predicts collection efficiencies greater than 99.6% for 10 μm diameter particles at relatively low values of current density and collection area [i.e., a current density of 10 nA/cm^2 and a collection area to volume flow ratio of 39.4 $m^2/(m^3/sec)$].

REMOVAL OF COLLECTED MATERIAL

In dry collection, the removal of the precipitated material from the collection plates and subsequent conveyance of the material away from the precipitator represent fundamental steps in the collection process. These steps are fundamental because collected material must be removed from the precipitator and because the buildup of excessively thick layers on the plates must be prevented in order to ensure optimum electrical operating conditions. Material which has been precipitated on the collection plates is usually dislodged by mechanical jarring or vibration of the plates, a process calling rapping. The dislodged material falls under the influence of gravity into hoppers located below the plates and is subsequently removed from the precipitator.

The effect of rapping on the collection process is determined primarily by the intensity and frequency of the force applied to the plates. Ideally, the rapping intensity must be large enough to remove a significant fraction of the collected material but not so large as to propel material back into the main gas stream. The rapping frequency must be adjusted so that a larger thickness which is easy to remove and does not significantly degrade the electrical conditions is reached between raps. In practice, the optimum rapping intensity and frequency must be determined by experimentation. With perfect rapping, the sheet of collected material would not reentrain, but would migrate down the collection plate in a stick-slip mode, sticking by the electrical holding forces and slipping when released by the rapping forces.

SECTION 5

LIMITING FACTORS AFFECTING PRECIPITATOR PERFORMANCE

ALLOWABLE VOLTAGE AND CURRENT DENSITY

The performance of a precipitator which has good mechanical and structural features will be determined primarily by the electrical operating conditions. Any limitations on applied voltage and current density will be reflected in the optimum collection efficiency which can be obtained. A precipitator should be operated at the highest useful values of applied voltage and current density for the following reasons:

(1) high applied voltages produce high electric fields;

(2) high electric fields produce high values of the saturation and limiting charge that a particle may obtain;

(3) high current densities produce high rates at which particles charge to the saturation or limiting values of charge;

(4) high current densities produce an increased electric field near the collection electrode due to the "ionic space charge" contribution to the field; and

(5) high values of electric field and particle charge produce high migration velocities and increased transport of particles to the collection electrode.

Electrical conditions in a precipitator are limited by either electrical breakdown of the gas in the interelectrode space or by electrical breakdown of the gas in the collected particulate layer. In a clean-gas, clean-plate environment, gas breakdown can originate at the collection electrode due to surface irregularities and edge effects which result in localized regions of high electric field. If the electric field in the interelectrode space is high enough, the gas breakdown will be evidenced by a spark which propagates across the interelectrode space. The operating applied voltage and current density will be limited by these sparking conditions.

If a particulate layer is deposited on the collection electrode, then the corona current must pass through the particulate layer to the grounded, collection electrode. The voltage drop (V_L) across the particulate layer is

$$V_L = j\rho' t \quad , \tag{3}$$

where j = current density (A/cm^2),

ρ' = resistivity of particulate layer (ohm-cm), and

t = thickness of the layer (cm).

The average electric field in the particulate layer (E_L) is given by

$$E_L = j\rho'. \tag{4}$$

The average electric field in the particulate layer can be increased to the point that the gas in the interstitial space breaks down electrically. This breakdown results from the acceleration of free electrons to ionization velocity to produce an avalanche condition similar to that at the corona electrode. When this breakdown occurs, one of two possible situations will ensue. If the electrical resistivity of the particulate layer is moderate ($\sim$0.1-1.0 x 10^{11} ohm-cm), then the applied voltage may be sufficiently high so that a spark will propagate across the interelectrode space. The rate of sparking for a given precipitator geometry will determine the operating electrical conditions in such a circumstance. If the electrical resistivity of the particulate layer is high ($>10^{11}$ ohm-cm), then the applied voltage may not be high enough to cause a spark to propagate across the interelectrode space. In this case, the particulate layer will be continuously broken down electrically and will discharge positive ions into the interelectrode space. This condition is called back corona. The effect of these positive ions is to reduce the amount of negative charge on a particle due to bipolar charging and reduce the electric field associated with the "ionic space charge". Both the magnitude of particle charge and rate of particle charging are affected by back corona. Useful precipitator current is therefore limited to values which occur prior to electrical breakdown whether the breakdown occurs as sparkover or back corona.

Field experience shows that current densities for cold side precipitators are limited to approximately 50-70 nA/cm^2 due to electrical breakdown of the gases in the interelectrode space. Consequently, this constitutes a current limit under conditions where breakdown of the particulate layer does not occur.

Electrical breakdown of the particulate layer has been studied extensively by Penney and Craig[12] and Pottinger[13] and can be influenced by many factors. Experimental measurements show that particulate layers experience electrical breakdown at average electric field strengths across the layers of approximately 5 kV/cm. Since it takes an electric field strength of approximately 30 kV/cm to cause electrical breakdown of air, the low breakdown strength of particulate layers suggests that high localized fields exist in the particulate layer and produce the breakdown of the gas in the layer. The presence of dielectric or conducting particles can cause localized regions of high electric field which constitute a negligible contribution to the average electric field across the layer. The size distribution of the collected particles also influences the electrical breakdown strength by changing the volume of interstices.[14] It has also been found that breakdown strength varies with particulate resistivity with the higher breakdown strength being associated with the higher resistivity.

METHODS FOR PREDICTING FLY ASH ELECTRICAL RESISTIVITY

Since the electrical resistivity has a pronounced effect on the electrostatic collectability of fly ash, it is desirable to have advanced knowledge regarding the magnitude of resistivity one might expect from a given coal. Obviously the best source of this information would be in situ resistivity measurements made during the burning of the subject coal in a commercial boiler. If the coal has not been used commercially, one has the option of burning the coal in a small scale pilot furnace and measuring the resistivity in situ or in the laboratory, or one can utilize one of the methods[15,16,17] for predicting fly ash resistivity.

These methods for predicting resistivity are based on correlations that have been established between resistivity and fly ash compositions for specific laboratory test conditions. The techniques leave much to be desired. First, although coal ash analyses can be used, the predictors are based on fly ash analyses. Second, the predictors do not take into account the effect of environmental variations. Presently, research[18] is being conducted to develop a predictive technique that will utilize the chemical composition of a coal ash and the stoichiometrically calculated flue gas.

NONIDEAL EFFECTS

The nonidealities which exist in full-scale electrostatic precipitators will reduce the ideal collection efficiency that may be achieved with a given specific collection area. The nonideal effects of major importance are (1) nonuniform gas velocity distribution, (2) gas sneakage, and (3) particle reentrainment. These nonideal effects must be minimized by proper design and optimization of a precipitator in order to avoid serious degradation in performance.

Nonuniform Gas Velocity Distribution

Uniform, low-turbulence gas flow is essential for optimum precipitator performance. Nonuniform gas flow through a precipitator lowers performance due to two effects. First, due to the exponential nature of the collection mechanism, it can be shown mathematically that uneven treatment of the gas lowers collection efficiency in the high velocity zones to an extent not compensated for in the low velocity zones. Secondly, high velocity regions near collection plates and in hopper areas can sweep particles back into the main gas stream.

Although it is known that a poor gas velocity distribution results in reduced collection efficiency, it is difficult to formulate a mathematical description for gas flow quality. White[19] discusses nonuniform gas flow and suggests corrective actions. Preszler and Lajos[20] assign a figure-of-merit based upon the relative kinetic energy of the actual velocity distribution compared to the kinetic energy of the average velocity. This figure-of-merit provides a measure of how difficult it may be to rectify the velocity distribution but not necessarily a measure of how much the precipitator performance would be degraded. At the inlet of a precipitator, a value of 0.25 or less for the ratio of the standard deviation of the gas velocity distribution to the average gas velocity is generally recommended. However, it must be noted that the gas velocity distribution can change significantly throughout the length of a precipitator and, depending upon the design of the precipitator and the manner in which it is interfaced with other plant equipment, the gas velocity distribution may improve or degrade.

Gas Sneakage

Gas sneakage occurs when gas bypasses the electrified regions of an electrostatic precipitator by flowing through the hoppers or through the high voltage insulation space. Gas sneakage can be reduced by the use of frequent baffles which force the gas to return to the main gas passages between the collection plates. If there were no baffles, the percent gas sneakage would establish the maximum possible collection efficiency because it would be the percent volume having zero collection efficiency. With baffles, the sneakage gas remixes with part of the main gas flow and then another fraction of the main gas flow re-bypasses in the next unbaffled region. The upper limit on collection efficiency due to gas sneakage will therefore depend on the amount of sneakage gas per baffled section, the degree of remixing, and the number of baffled sections. Gas sneakage becomes increasingly important for precipitators designed for high collection efficiencies where only a small amount of gas sneakage per section can result in a severe limitation on collection efficiency.

Particle Reentrainment

Particle reentrainment occurs when collected material reenters the main gas stream. This can be caused by several different effects and, in certain cases, can severely reduce the collection efficiency of a precipitator. Causes of particle reentrainment include (1) rapping which propels collected material into the interelectrode space, (2) the action of the flowing gas stream on the collected particulate layer, (3) sweepage of material from hoppers due to poor gas flow conditions, air inleakage into the hoppers, or the boiling effect of rapped material falling into the hoppers, and (4) excessive sparking which dislodges collected material by electrical impulses and disruptions in the current which is necessary to provide the electrical force which holds the material to the collection plates.

Recent studies[4,21] have been made to determine the effect of particle reentrainment on precipitator performance. In studies where the rappers were not employed, real-time measurements of outlet emissions at some installations showed that significant reentrainment of mass was occurring due to factors other than rapping. These same studies also showed that for high-efficiency, full-scale precipitators approximately 30-85% of the outlet particulate emissions could be attributed to rapping reentrainment. The results of these studies show that particle reentrainment, especially rapping reentrainment, is a significant factor in limiting precipitator performance.

SECTION 6

DESCRIPTION OF THE MATHEMATICAL MODEL

IDEAL CALCULATION OF PARTICLE COLLECTION EFFICIENCY

The mathematical model of electrostatic precipitation is based on the exponential-type relationship given in equation (2). This equation was derived subject to several assumptions which have been stated earlier. In order to use the equation it is necessary to structure the mathematical model such that the assumptions are not violated. As discussed earlier, the assumptions are never completely satisfied in an industrial precipitator but they can be approached closely.

The assumption that the particle migration velocity near the collection surface is constant for all particles has the most significant effect on the structure of the model. This assumption implies two things:

(1) The particles are all of the same diameter.

(2) The electrical conditions are constant.

Because the particles entering a precipitator are not all of the same diameter, the assumption of uniform particle diameters creates a problem. This problem is dealt with in the model by performing all calculations for single diameter particles and then summing the results to determine the effect of the electrostatic precipitation process on the entire particle size distribution.

Because the electrical conditions change along the length of a precipitator, the assumption of constant electrical conditions creates a problem. This problem is dealt with in the model by dividing the precipitator into small length increments. These length increments can be made small enough that the electrical conditions remain essentially constant over the increment. The number of particles of a given diameter which are collected in the different length increments are summed to determine the collection efficiency of particles of a single diameter over the entire length of the precipitator.

In summary, a precipitator is divided into essentially many small precipitators in series. Equation (2) is valid in each of these small precipitators for particles of a given diameter. A large majority of the time used in the computer program which performs the calculations in the model is devoted to calculating the values of quantities needed to determine the migration velocity for each particle diameter in each length increment.

The collection fraction, $\eta_{i,j}$, for the i-th particle size in the j-th increment of length of the precipitator is mathematically represented in the form

$$\eta_{i,j} = 1 - \exp\left(^{-w}i,j\ ^{A}j/^{Q}\right) \quad , \tag{5}$$

where $w_{i,j}$ (m/sec) is the migration velocity of the i-th particle size in the j-th increment of length and A_j (m^2) is the collection plate area in the j-th increment of length.

The collection fraction (fractional efficiency) η_i for a given particle size over the entire length of the precipitator is determined from

$$\eta_i = \frac{\sum_j \eta_{i,j} N_{i,j}}{N_{i,1}} \quad , \tag{6}$$

where $N_{i,j}$ is the number of particles of the i-th particle size per cubic meter of gas entering the j-th increment. The quantity $N_{i,j}$ can be written in the form

$$N_{i,j} = N_{i,j-1} \exp\left(^{-w}i,j-1\ ^{A}j-1/^{Q}\right) \quad , \tag{7}$$

where $N_{i,1} = N_{i,0}$, the number of particles of the i-th particle size per cubic meter of gas in the inlet size distribution which is expressed in the form of a histogram.

The overall mass collection efficiency η for the entire polydisperse aerosol is obtained from

$$\eta = \sum_i \eta_i P_i \quad , \tag{8}$$

where P_i is the percentage by mass of the i-th particle size in the inlet size distribution.

In order to determine the migration velocities for use in equation (5), the electrical conditions and the particle charging process in a precipitator must be modeled.

Calculation of Electrical Conditions

If the operating voltage and current are known and a voltage-current curve is not desired, then the electric potential and electric field distributions are determined by using a relaxation technique described by Leutert and Böhlen.[1,22] In this numerical technique, the appropriate partial differential equations which describe the electrodynamic field are solved simultaneously under boundary conditions existing in a wire-plate geometry. The equations which must be solved are written in discrete form in two dimensions as

$$\frac{\Delta^2 V}{\Delta x^2} + \frac{\Delta^2 V}{\Delta y^2} = -\frac{\rho}{\varepsilon_0} \quad \text{, and} \tag{9}$$

$$\rho^2 = \varepsilon_0 \left(\frac{\Delta V}{\Delta x}\frac{\Delta \rho}{\Delta x} + \frac{\Delta V}{\Delta y}\frac{\Delta \rho}{\Delta y}\right) + \frac{\varepsilon_0 \rho}{b_e}\left(\frac{\Delta V}{\Delta x}\frac{\Delta b_e}{\Delta x} + \frac{\Delta V}{\Delta y}\frac{\Delta b_e}{\Delta y}\right) \quad , \tag{10}$$

where ρ = space charge density (coul/m^3),

b_e = effective charge carrier mobility (m^2/V-sec),

y = coordinate parallel to gas flow from wire-to-wire (m),

x = coordinate perpendicular to gas flow from wire-to-plate (m), and

ε_0 = permittivity of free space (coul/N-m^2).

In order to find the solutions for V and ρ from equations (9) and (10), the known boundary conditions on applied voltage and current are held fixed while the space charge density at the wire is adjusted until all the boundary conditions are satisfied. For each choice of space charge density at the wire, the procedure iterates on a grid of electric potential and space charge density until convergence is obtained and then checks to see if the boundary condition on the average current density at the plate is met by using the expression

$$J_p = \left(b_e \sum_{i=1}^{N} \rho_{pi} E_{pi}\right)/N \quad , \tag{11}$$

where J_p = average current density at the plate (A/m^2),

b_e = effective charge carrier mobility ($m^2/V\text{-sec}$),

ρ_{pi} = space charge densities for points on the plate ($coul/m^3$),

E_{pi} = electric field strengths for points on the plate (V/m), and

N = number of grid points in the direction of gas flow.

If the boundary condition on the average current density at the plate is not met, then the space charge density at the wire is adjusted and the iteration procedure is repeated.

If the operating voltage and current are unknown or if a voltage-current curve is desired, then the voltage-current characteristic for a wire-plate geometry is determined by using the technique described by McDonald et al.[23] In this technique, the electric potential and electric field distributions are determined for each point on the voltage-current curve. Equations (9) and (10) are solved simultaneously using the same mathematical procedure employed by Leutert and Böhlen but an alternate set of boundary conditions is imposed. The space charge density in the region of ionization near the discharge electrode is calculated from an arbitrarily chosen value of average current density at the plate. The space charge density near the wire and the average current density at the plate provide boundary conditions which are held fixed while the electric potential at the wire is adjusted until simultaneous solutions are found to equations (9) and (10) which satisfy all the boundary conditions.

Calculation of Particle Charge

Particle charge is calculated from a unipolar, ionic-charging theory formulated by Smith and McDonald.[24] In this theory, particle charge is predicted as a function of particle diameter, exposure time, and electrical conditions. The charging equation is derived based on concepts from kinetic theory and determines the charging rate in terms of the probability of collisions between particles and ions. The theory accounts simultaneously for the effects of field and thermal charging and accounts for the effects of the applied electric field on the thermal charging process. According to this theory, the charging rate is given by

$$
\begin{aligned}
\frac{dq}{dt} = {} & \frac{N_0 e b q_s}{4\varepsilon_0} \left(1 - \frac{q}{q_s}\right)^2 \\
& + \frac{\pi a^2 \tilde{v} N_0 e}{2} \int_{\theta_0}^{\pi/2} \exp \left[\left(\frac{q e (r_0 - a)}{4\pi\varepsilon_0 k T a r_0} \right.\right. \\
& \left.\left. + \frac{[3 a r_0^2 - r_0^3 (K + 2) + a^3 (K - 1)] e E_0 \cos\theta}{k T r_0^2 \; (K + 2)} \right) \right] \sin\theta \, d\theta \\
& + \frac{\pi a^2 \tilde{v} N_0 e}{2} \exp\left(-qe/4\pi\varepsilon_0 a k T\right) \quad ,
\end{aligned} \tag{12}
$$

where $q_s = 4\pi\varepsilon_0 E_0 a^2 \left(1 + 2\,\frac{K-1}{K+2}\right)$, (13)

$\theta_0 = \arccos\,(q/q_s)$, (14)

and q = instantaneous charge on the particle (coul),

q_s = saturation charge due to field charging (coul),

θ = azimuthal angle in a spherical coordinate system with origin at the center of the particle (radians),

θ_0 = maximum azimuthal angle for which electric field lines enter the particle (radians),

N_0 = free ion density (m^{-3}),

e = electronic charge (coul),

ε_0 = permittivity of free space (coul/V-m),

E_0 = average electric field between the electrodes (V/m),

b = ion mobility (m^2/V-sec),

$\tilde{v}$ = mean thermal speed of ions (m/sec),

a = particle radius (m),

k = Boltzmann's constant (J/°K),

T = absolute temperature (°K),

t = time (sec),

K = dielectric constant of the particle, and

r_0 = radial distance along θ at which the radial component of the total electric field is zero (m).

For large particles and high applied electric fields, the theory predicts essentially the same charging rate as the classical field charging equation. For low applied electric fields, the charging equation reduces to the classical thermal equation.

Equation (12) can be solved on a computer by simple numerical techniques. The integral on the right-hand side of equation (12) is evaluated using Simpson's Rule and the charge as a function of time is determined by using the quartic Runge-Kutta method.

In cases where the use of computer time is an important consideration, the computer model for electrostatic precipitation allows for considerable savings in computer time by providing the option of using an analytical expression for charge as a function of time. This expression is given by

$$\begin{aligned} q &= q_D + q_F \\ &= \left(\frac{4\pi\varepsilon_0 akT}{e}\right) \ln \left[\left(\frac{e^2 a\tilde{v}N_0}{4\varepsilon_0 kT}\right) \left(t_f - t_i\right) + \mathrm{Exp}\left(\frac{q_i e}{4\pi\varepsilon_0 akT}\right) \right] \\ &\quad + q_s \left[\frac{\left(\frac{N_0 be}{4\varepsilon_0}\right)\left(t_f - t_i\right) + \frac{1}{(1 - q_i/q_s)} - 1}{\left(\frac{N_0 be}{4\varepsilon_0}\right)\left(t_f - t_i\right) + \frac{1}{(1 - q_i/q_s)}} \right] , \qquad (15) \end{aligned}$$

where q_D = charge predicted from classical diffusion charging theory (coul),

q_F = charge predicted from classical field charging theory (coul),

t_i = initial time for charging under a fixed set of conditions (sec),

t_f = final time for charging under a fixed set of conditions (sec),

q_i = charge on the particle at t_i (coul),

and all other symbols are as defined previously.

This equation represents the sum of the charges from classical field and diffusion charging theories. In principle, the sum of the charging rates should be added to be physically meaningful; however, fortuitously, equation (15) yields a reasonable prediction of particle charge for particles in the size range 0.09-1.4 μm in diameter.[25] The forms of q_D and q_F used in equation (15) reflect the fact that N_0 and E_0 change along the length of a precipitator and, in the model, are assumed to remain fixed only over each incremental length.

Calculation of Space Charge Effects

In the calculation of the electrical conditions, it is assumed that the motion of all the charge carriers can, on the average, be described by a single "effective mobility". The presence of particles in the flue gas will cause a reduction in the "effective mobility" because the particles, which acquire charge from the ions and are much less mobile than ions, must carry part of the total current.[1,26,27] When the electrical conditions are calculated by using measured values of applied voltage and current density, the "effective mobility" is determined from[1,26]

$$b_e = b' \left(\frac{j_t}{200\ j_p + j_t} \right) , \qquad (16)$$

where b_e = effective mobility for ions and particles (m^2/V-sec),

b' = effective ion mobility (m^2/V-sec),

j_t = total current density at the plate (A/m^2), and

j_p = particulate current density at the plate (A/m^2).

If the electrical conditions are calculated by generating a voltage-current curve, then the model employs a different method for determining the effects of space charge. Since this method has not been published prior to this writing, it is discussed in Appendix A in more detail than the other calculations which are presented. In this part of the text, this method will be discussed only briefly in order to acquaint the reader with the basic concepts involved in the method.

In this method, the precipitator is divided into successive length increments which are equal to the wire-to-wire spacing. Each of these increments is divided into several subincrements. The first calculation in the procedure involves the determination of a clean-gas, voltage-current curve which terminates at some specified value of applied voltage. At the specified applied voltage, the average electric field and ion density are calculated in each subincrement. This allows for the nonuniformity of the electric field and current density distributions to be taken into account.

As initially uncharged particles enter and proceed through the precipitator, the mechanisms of particle charging and particle collection are considered in each subincrement. In each subincrement, the average ion density, average particulate density, weighted particulate mobility, and effective mobility due to both ions and particles are determined. At the end of each increment, the effective mobilities for the subincrements are averaged in order to obtain an average effective mobility for the increment. Then, for the specified value of applied voltage, the average effective mobility is used to determine the reduced current for the increment by either calculating a new voltage-current curve or using an approximation which is discussed in Appendix A.

In its present state of development, this method provides good estimates of reduced current due to the presence of particles. However, it does not have the capability of predicting the redistribution of the electric field due to the presence of particles. Work is going on at the present time to improve the model in this respect. This work involves the use of an iteration procedure over each increment in order to obtain self-consistency.

METHODS FOR ESTIMATING NONIDEAL EFFECTS

Since the model is structured around an exponential-type equation for individual particle sizes, it is convenient to represent the effect of the nonidealities in the model as correction factors which apply to the exponential argument. These correction factors are used as divisors for the ideally-calculated effective migration velocities.

Since four types of migration velocities will be referred to in the following sections, it is important to define the terminology which will be used. The migration velocity w is a quantity which is calculated from fundamental principles and applies only to a given length increment as used in the model. This quantity represents the actual drift velocity of a particle toward the collection electrode in the region near the collection electrode. The effective or length-averaged migration velocity w_e is a quantity which is calculated from fundamental principles but it applies to the entire length of the precipitator. This quantity is obtained by replacing w_p in equation (2) by w_e and determining a single value of w_e which is necessary to produce the same collection efficiency over the entire length of the precipitator that is obtained from the values of w. The apparent effective migration velocity w_e' is a quantity which is obtained from making an empirical correction (or corrections) to the effective migration velocity w_e. This quantity bears no relationship to the actual migration velocities in the region of space adjacent to the collection electrode and has no physical interpretation. The quantities w, w_e, and w_e' apply to particles of a given diameter. The precipitation rate parameter w_{pr} is a quantity which provides a measure of how well the entire mass which enters the precipitator will be collected. This quantity is obtained by replacing w_p in equation (2) by w_{pr} and determining a single value of w_{pr} which is necessary to produce the same overall mass collection efficiency that is obtained from the collection efficiencies for all particle diameters, as determined by the values of w_e or w_e', and the inlet particle size distribution.

Calculation of Effect of Nonuniform Velocity Distribution

It is possible to develop an approach to estimating the degradation of performance due to a nonuniform velocity distribution based upon the velocity distribution, the ideal collection efficiencies, and the exponential-type collection equation.[1] In this approach, it is assumed that equation (2) applies to each particle size with a known effective migration velocity and that the specific collecting area and size of the precipitator are fixed.

For any practical velocity distribution and efficiency, the mean penetration obtained by summation over the point values of velocity will be higher than the penetration calculated from the average velocity. If an effective migration velocity for a given particle size is calculated based upon the mean penetration and equation (2), the resulting effective migration velocity will have a value lower than the value necessary to obtain the same mean penetration from a summation of point values of penetration. The ratio of the effective migration velocity determined by the summation of point values of penetration to that determined by equation (2) is a numerical measure of the performance degradation caused by a nonuniform velocity distribution. An expression for this ratio may be obtained by setting the penetration based on the average velocity equal to the corrected penetration obtained from a summation of the point values of penetration and solving for the required correction factor, which will be a divisor for the effective migration velocity obtained from equation (2).

Whether the correction factor obtained from the above procedure correlates reasonably well with statistical measures of velocity nonuniformity is yet to be established. A limited number of traverse calculations which have been performed seem to indicate a correlation between the correction factor and the normalized standard deviation of the velocity traverse. Based upon a pilot plant study,[20] the following empirical relationship between the correction factors F_i, the normalized standard deviation of the velocity distribution σ_g, and the ideal collection fractions η_i for the i-th particle size under consideration has been obtained:[1]

$$F_i = 1 + 0.766\ \eta_i \sigma_g^{1.786} + 0.0755\ \sigma_g \ln (1/1-\eta_i). \qquad (17)$$

In simulating the performance of a particular precipitator, the preferred procedure would be to obtain the relationship $[F_i = F_i\ (\eta_i, \sigma_g)]$ between F_i, η_i, and σ_g for the conditions to be simulated from a velocity traverse at the entrance to the precipitator. If this cannot be done, equation (17) can be used, but only in the sense of obtaining a rough estimate of the effects of a given nonuniform velocity distribution.

Calculation of Effect of Gas Sneakage

If the simplifying assumption is made that perfect mixing occurs following each baffled section, then an expression for the penetration P_{N_S} of a given particle size from the last baffled section which is corrected for gas sneakage can be derived[1] in the form

$$P_{N_S} = [S + (1-S)(1-\eta_i)^{1/N_s}]^{N_s} \quad , \qquad (18)$$

where S is the fractional amount of gas sneakage per baffled section and N_s is the number of baffled sections. Estimations based on equation (18) indicate that, for high efficiencies, the number of baffled sections should be at least four and the amount of sneakage should be held to a low percentage. With a high percentage of sneakage, even a large number of baffled sections fail to help significantly.

Gas sneakage factors B_i can be defined in the form of divisors for the effective, or length-averaged, migration velocities in the exponential argument of equation (2). The factors B_i are obtained by taking the ratio of the effective migration velocities $w_{e,i}$ under ideal conditions to the apparent effective migration velocities $w'_{e,i}$ under conditions of gas sneakage so that

$$B_i = \frac{w_{e,i}}{w'_{e,i}} = \frac{\ln (1-\eta_i)}{\ln P_{N_S}} = \frac{\ln (1-\eta_i)}{N_s \ln [S + (1-S)(1-\eta_i)^{1/N_s}]} , \quad (19)$$

where the subscript i refers to the different particle diameters.

The foregoing estimation of the effects of gas sneakage is a simplification in that the sneakage gas passing the baffles will not necessarily mix perfectly with the main gas flow and the flow pattern of the gas in the bypass zones will not be uniform and constant. Equation (18) has been formulated to help in designing and analyzing precipitators by establishing the order of magnitude of the problem. Considerable experimental data will be required in order to evaluate the method and to establish numerical values of actual sneakage rates.

Calculation of Effect of Reentrainment Without Rapping

Although it is difficult to quantify the complex mechanisms associated with particle reentrainment due to (1) the action of the flowing gas stream on the collected particulate layer, (2) sweepage of particles from hoppers caused by poor gas flow conditions or air inleakage into the hoppers, and (3) excessive sparking, the effect of these nonideal conditions on precipitator performance can be estimated if some simplifying assumptions are made. If it is assumed that a fixed fraction of the collected material of a given particle size is reentrained and that the fraction does not vary with length through the precipitator, an expression can be derived which is identical in form to that obtained for gas sneakage:[1]

$$P_{N_R} = [R + (1-R)1-\eta_i)^{1/N_R}]^{N_R} , \quad (20)$$

where P_{N_R} is the penetration of a given particle size corrected for reentrainment, R is the fraction of material reentrained, and N_R is the number of stages over which reentrainment is assumed to occur.

Since equations (18) and (20) are of the same form, the effect of particle reentrainment without rapping can be expected to be similar to the effect of gas sneakage, provided that a constant fraction of the collected material is reentrained in each stage. It is doubtful that such a condition exists, since the gas flow pattern changes throughout the precipitator and different holding forces and spark rates exist in different electrical sections. However, until detailed studies are made to quantify the losses in collection efficiency as a function of particle size for these types of reentrainment, equation (20) provides a means of estimating the effect of particle reentrainment without rapping on precipitator performance.

Since the equation which is obtained for calculating the correction factors for particle reentrainment without rapping is of the same form as that obtained for calculating the correction factors for gas sneakage, only equation (19) is used in the model. Thus, only a value of S is used as input data for the model. However, the value of S represents the combined effects of the fractional amount of gas sneakage per baffled section and the fractional amount of collected material which is reentrained per baffled section without rapping.

No-Rap Calculations

The combined nonideal effects of nonuniform gas velocity distribution, gas sneakage, and particle reentrainment without rapping are taken into account by reducing the ideally calculated effective migration velocities $w_{e,i}$ by the correction factors F_i and B_i. Apparent effective migration velocities $w'_{e,i}$ are determined from

$$w'_{e,i} = \frac{w_{e,i}}{F_i \cdot B_i} \quad , \tag{21}$$

where the subscript i refers to the different particle diameters. Corrected fractional collection efficiencies are calculated using equation (2) and the values of the $w'_{e,i}$.

The apparent effective migration velocities and corresponding collection efficiencies obtained from equation (21) may be referred to as "no-rap" migration velocities and collection efficiencies. These quantities are of practical interest because they can be measured by turning the rappers off, whereas ideal quantities can never be truly measured.

Calculation of Effect of Rapping Reentrainment

As part of a program sponsored by the Electric Power Research Institute, an approach to representing losses in collection efficiency due to rapping reentrainment has been developed based upon studies performed on six different full-scale precipitators collecting fly ash.[4] In these studies, outlet mass loadings and particle size distributions were measured both with rapping losses and without rapping losses. Based on these data, outlet mass loadings and particle size distributions which can be attributed to rapping were obtained.

The rapping emissions obtained from the measurements on the six precipitators are graphed in Figure 4 as a function of the amount of dust calculated to have been removed by the last electrical section. The dust removal in the last electrical section was approximated by

$$\eta'/\text{section} = 1-\exp(-X'/N_E) \quad , \tag{22}$$

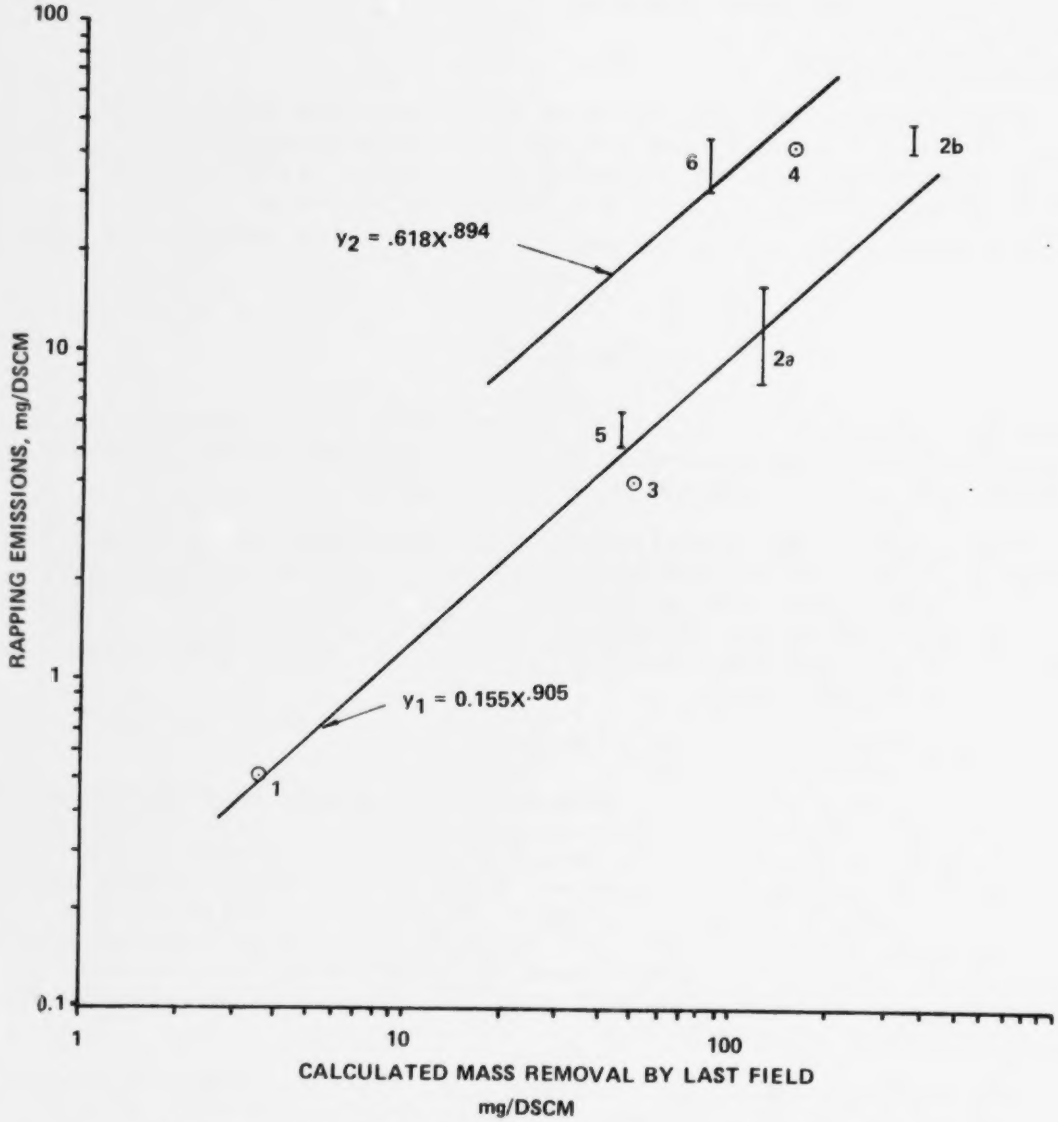


Figure 4. Measured rapping emissions versus calculated particulate removal by last electrical section. These curves are a result of work sponsored by the Electric Power Research Institute.

where $X' = -\ln(1-\eta_0)$, (23)

η_0 = overall mass collection fraction determined from mass train measurements under normal operating conditions, and

N_E = number of electrical sections in series.

These data suggest a correlation between rapping losses and particulate collection rate in the last electrical section. Data for the two hot-side installations (4 and 6) which were tested show higher rapping losses than for the cold-side units. This would be expected due to reduced dust adhesivity at higher temperatures. Data 2a and 2b are for a cold-side unit operating at normal and approximately one-half normal current density, respectively. The decrease in current density at installation 2 resulted in a significant increase in rapping emissions due to the increased mass collected in the last field and smaller electrical holding force for the same rapping intensity.

The simple exponential relationships

$$y_1 = (0.155)X^{0.905} \quad (24)$$

and

$$y_2 = (0.618)X^{0.894} \quad (25)$$

can be used for interpolation purposes in determining the rapping emissions (mg/DSCM) for a given calculated mass removed by the last field (mg/DSCM) for cold- and hot-side precipitators, respectively. In constructing Figure 4, the calculated mass removed in the last field was determined by using the measured overall mass collection efficiency during normal operation of the precipitator. This was done because complete traverses were made by the mass trains during the normal tests whereas this was not the case for the measurements made during the no-rap tests. In principle, the no-rap efficiencies should be used to calculate the mass removed in the last field and this is what is done in the mathematical model. Obviously, the limited amount of data obtained thus far is not sufficient to validate in general the approach presented here. However, this approach gives reasonable agreement with the existing data and offers a quantitative method for estimating rapping losses.

The apparent size distribution of emissions attributable to rapping at each installation was obtained by subtracting the cumulative distributions during non-rapping periods from those with rappers in operation, and dividing by the total emissions (based on impactor measurements) resulting from rapping in order to obtain a cumulative percent distribution. Figure 5 contains the results of these calculations. Although the data indicate considerable scatter, an average particle size distribution has been constructed in Figure 6 for use in modeling rapping puffs. In the mathematical model, the data in Figure 6 are approximated by a log-normal distribution with a mass median diameter of 6.0 μm and a geometric standard deviation of 2.5.

In summary, the mathematical model determines a "rapping puff" by using either equation (24) or (25) to obtain the outlet mass loading due to rapping and by using a log-normal approximation to the data in Figure 6 to represent the particle size distribution of the outlet mass loading due to rapping. This "rapping puff" is added to the "no-rap" outlet emissions to obtain the total outlet emissions as a function of mass loading and particle size distribution. Then, the model generates migration velocity, collection efficiency, penetration, and $\Delta M/\Delta \log D$ (rate of change of mass over a given size interval) as a function of particle diameter for the "no-rap", "rapping puff" and "no-rap" plus "rapping puff" outlet emissions.

Although rapping is an important part of the electrostatic precipitation process, the present version of the model does not take into account the temporal and dynamic nature of the rapping process. The time-dependent aspects of the rapping process are of significance because different electrical sections are rapped at different time intervals and the thickness of the collected particulate layer changes with time. The dynamic aspects of the rapping process are of significance because (1) a suitable mechanical force must be applied to a collection electrode in order to remove the collected particulate layer, (2) the force which is necessary to remove the collected particulate layer from the collection electrode depends on such variables as the electrical forces in the layer, the cohesiveness and adhesiveness, etc., and (3) the reentrained particles are recharged and re-collected as the gas flow carries them downstream. Although the empirical procedure employed in the present version of the model represents a useful interim technique for estimating the effects due to rapping reentrainment in precipitators, it is important that models be developed in the future to describe the temporal and dynamic aspects of the rapping process.

EMPIRICAL CORRECTIONS TO NO-RAP MIGRATION VELOCITIES

Comparisons of measured apparent effective migration velocities for full-scale precipitators under "no-rap" conditions with those predicted by the model indicate that the field-measured values exceed the theoretically projected values (in the absence of back corona, excessive sparking, or severe mechanical problems) in the smaller size range. Based on these comparisons, a size-dependent correction factor has been constructed and incorporated

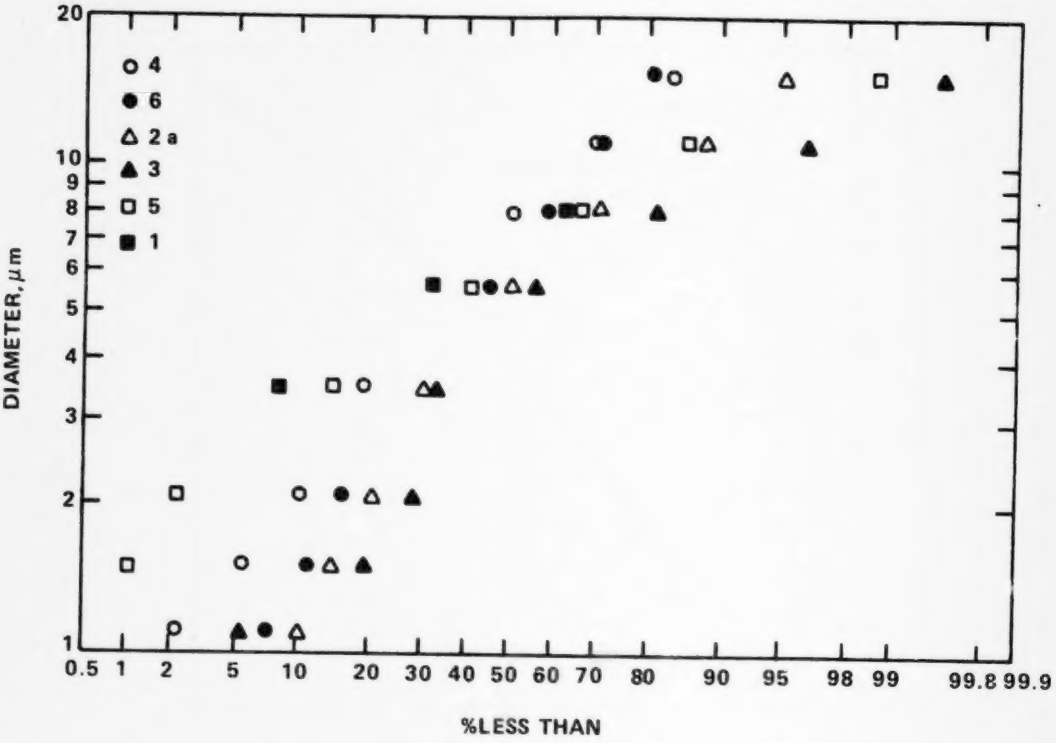


Figure 5. Apparent rapping puff size distribution for six full-scale precipitators. These data are a result of work sponsored by the Electric Power Research Institute.

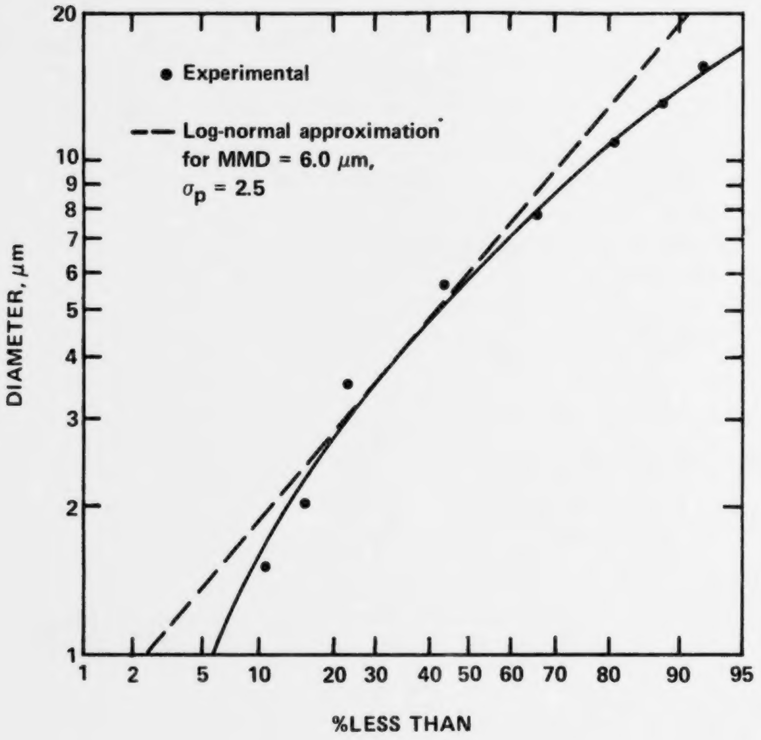


Figure 6. Average rapping puff size distribution for six full-scale precipitators. These data are a result of work sponsored by the Electric Power Research Institute.

into the model.[4] This correction factor is shown in Figure 7.

The empirical correction factor accounts for those effects which enhance particle collection efficiency but are not included in the present model. These effects include particle charging near corona wires, particle concentration gradients, and flow field phenomena. In future work which is planned, efforts will be made to develop theoretical relationships to describe the above effects and to incorporate them into a more comprehensive model for electrostatic precipitation.

ESTIMATION PROCEDURE FOR CALCULATING PARTICLE COLLECTION EFFICIENCIES

The mathematical model for electrostatic precipitation allows for the use of estimation procedures for calculating particle collection efficiencies. Use of these procedures results in considerable savings in computer time since involved numerical techniques are not extensively employed. These procedures can be used to advantage when only gross trends in precipitator performance are required or when an estimating technique is desired in order to approximate the specific collection area required for a chosen overall mass collection efficiency so that a starting point for the more rigorous calculation can be easily obtained.

In the case where the operating applied voltage and current are known, particle charge, average electric field at the plate, and space charge effects are only estimated. Particle charge is calculated by using equation (15). The average electric field at the plate is calculated by dividing the applied voltage by the wire-to-plate spacing and scaling this value down by a factor of 1.75. This method of determining the average electric field at the plate is based on the examination of the results from model simulations of several full-scale precipitators which were collecting fly ash. Space charge effects are determined by reducing the free ion density and effective charge carrier mobility in the same procedure which leads to equation (16).

In the case where the operating applied voltage and current are not known, a voltage-current curve must be generated up to some specified operating applied voltage. The voltage-current calculation also determines the average electric field at the plate which is used in the estimation procedure. Particle charge is calculated by using equation (15). Space charge effects are determined by applying the new procedure discussed earlier and in Appendix A.

It must be emphasized that these procedures are not expected to give results which will always be reasonable estimates. For any given set of conditions, these procedures may lead to predictions of precipitator performance which are in considerable error. However, in most cases, they should yield reasonable

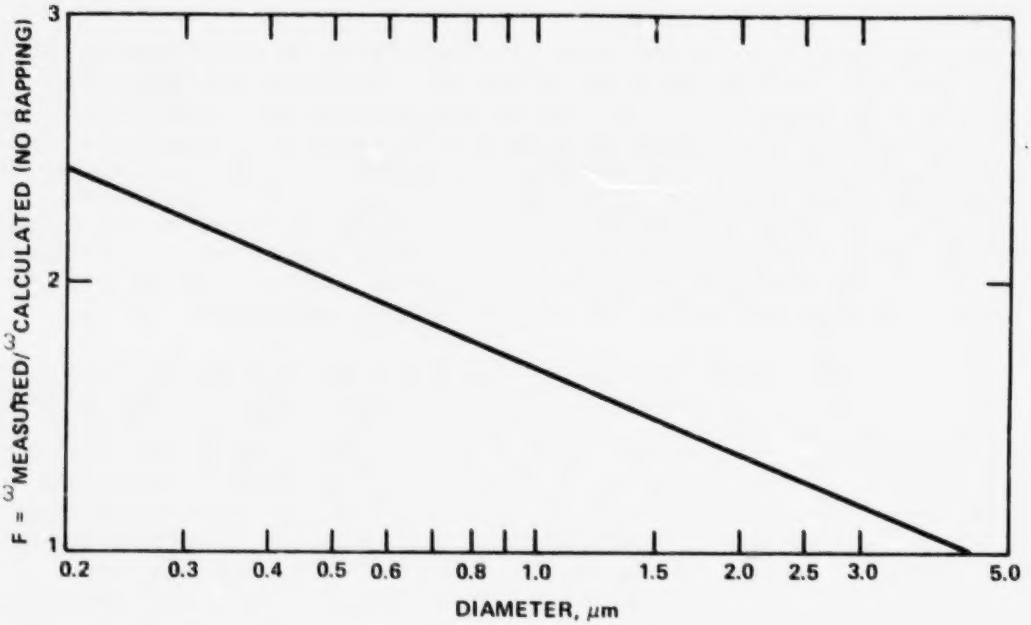


Figure 7. Empirical correction factors for the "no-rap" migration velocities calculated from the mathematical model. This work was sponsored by the Electric Power Research Institute.

estimates of precipitator performance and their judicious use can lead to considerable savings in computer time.

SECTION 7

COMPUTER PROGRAMING OF THE MATHEMATICAL MODEL

DESCRIPTION OF THE COMPUTER PROGRAM

A computer program has been written in Fortran IV language in order to perform the mathematical operations associated with the model of electrostatic precipitation discussed in Section 6. Although the program has been developed using a Digital Equipment Corporation, PDP 15/76 computer, efforts have been made to make the program sufficiently generalized so that it can be easily implemented on other computers which have a Fortran compiler. Due to the lack of sufficient storage capacity on the PDP 15/76 computer, the program contains some duplication because the use of arrays for storing the values of certain variables is avoided and the values of these variables are recalculated each time they are needed in the program. Appendix B contains a list of the symbols used in the program along with their definitions and Appendix C contains a listing of the entire program. The program consists of a main program and 20 subroutines. Excluding job control language (JCL) cards, the program card deck contains 2,240 cards.

The following is a sequential list of the major operations which are performed by the computer program in order to determine fractional collection efficiencies and overall mass collection efficiency.

1. Data which are necessary to characterize precipitator performance are read into the main program.

2. If the inlet size distribution is known, it is read into the main program in the form of a histogram and it is "fit" to a log-normal distribution in subroutine LNFIT. Alternatively, parameters characteristic of a log-normal distribution can be read into the main program and a histogram is constructed in subroutine LNDIST in order to represent the inlet size distribution.

3. The number of particles in each size band of the inlet size distribution is calculated.

4. The precipitator is divided into specified incremental lengths.

5. If the operating applied voltage and current are not known, then subroutine EFLD2 is used to generate a clean-plate, clean-gas, voltage-current curve up to a specified value of operating applied voltage, to determine the free ion densities and charging fields for particle charging, and to calculate the electric field at the plate. If the operating applied voltage and current density are known, then subroutine SPCHG1 is used to calculate the amount of material removed per increment and the "particulate space charge" in each increment based on an estimated overall mass collection efficiency, to determine an effective charge carrier mobility, and to establish a reduced free ion density in each increment for use in determining particle charge.

6. If the operating applied voltage and current are known, then the average charging field is calculated using the applied voltage and the wire-to-plate spacing and the electric field at the plate is calculated in subroutine EFLD1.

7. The charge on each particle size at the end of each increment or subincrement of length is calculated in either CHARGN or by using equation (15), whichever is specified. In order to save computer time, the program contains a procedure which bypasses the charge calculation for a given particle size whenever the charge on that size does not change by more than 0.5% in two successive length increments in the same electrical section. Also, if the charge calculation for a given particle size has been bypassed in the last increment of a given electrical section and the applied voltage in this section is equal to or greater than that in the next section, then the charge calculation for this particle size will be bypassed in each increment in the next section.

8. If the operating applied voltage and current are unknown, then subroutine SPCHG2 is used to determine the "particulate space charge", the effective charge carrier mobility, and the operating current density.

9. A migration velocity for each particle size is calculated at the end of each length increment using equation (1).

10. The number of particles removed in each size band after each length increment of travel is calculated using equation (2).

11. After the required calculations have been performed in all length increments, an overall mass collection efficiency is calculated. If the operating applied voltage and current are known, then the calculated overall mass collection efficiency is compared with the input estimated efficiency. If the difference is greater than 0.05%, the program returns to the first length increment and repeats all calculations using the newly computed overall mass collection efficiency. Usually, only one iteration

is required. If the calculation of the overall mass collection efficiency has been based on a generated voltage-current curve, then no iteration over incremental lengths is performed.

12. After the overall mass collection efficiency has been obtained, an "effective" migration velocity is calculated for each size band and a precipitation rate parameter is computed based on the overall mass collection efficiency and equation (2).

The above operations complete the calculation of ideal performance that would be expected under a given set of input conditions and based on those physical mechanisms which are included in the model. In the following operations which are performed in subroutine ADJUST, corrections are made to the ideal projections by operating on the "effective" migration velocity for each particle size in order to account for unmodeled and nonideal effects.

13. For a given value of normalized gas velocity standard deviation, a correction factor is calculated for each "effective" migration velocity using the ideal efficiency for a given particle size and equation (17).

14. Using assumed values of number of stages and the percent loss per stage from reentrainment without rapping and/or gas sneakage, a correction factor is calculated for each "effective" migration velocity using the ideal efficiency for a given particle size and equation (19).

15. An "apparent" effective, no-rap migration velocity is obtained for each particle size by dividing the ideal values by the product of the two correction factors described above and a no-rap collection efficiency is calculated for each particle size using equation (2).

16. Using the correction factors given in Figure 7, subroutine WADJST corrects the "apparent" effective, no-rap migration velocities in order to account for unmodeled effects and "adjusted" no-rap efficiencies are determined. An "adjusted" no-rap overall mass collection efficiency and precipitation rate parameter are calculated.

17. Losses in collection efficiency due to rapping reentrainment are obtained by reducing the mass collected in each size band under "adjusted" no-rap conditions according to either equation (24) or (25) and Figure 6. A collection efficiency and migration velocity with rapping are calculated for each particle size. An overall mass collection efficiency and precipitation rate parameter which account for losses due to rapping are calculated.

18. No-rap and no-rap + rap outlet size distributions are determined and outlet emissions are characterized by calculation

of $\Delta M/\Delta \log D$ for each size band for the "rapping puff" and no-rap and no-rap + rap conditions.

19. No-rap and no-rap + rap outlet size distributions are "fit" to a log-normal distribution.

20. All input data and relevant parameters which have been calculated are printed.

In Figure 8, a simplified flow chart for the main program is given. This flow chart shows the major operations and logic branches and all subroutine callings. The input and output data for the computer program, along with the various uses of the program, will be discussed in detail in Volume 2 of this report. In the following subsection, the subroutines which are called by the main program will be discussed in detail.

DESCRIPTIONS OF THE SUBROUTINES

Subroutine SPCHG1

This subroutine determines the effect of "particulate space charge" in each increment of length by using the procedure leading to equation (16) in order to calculate an "effective" charge carrier mobility and average reduced ion density for particle charging. Figure 9 shows a detailed flow chart for this subroutine. All information which is transmitted between the main program and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

SW - Estimated sum of material removed in successive increments of the ESP (kg/m^3).

ROVRI - Ratio of total charge density to ionic charge density in a given increment of the ESP. Initialized to 10.0 to start procedure.

OROVRI - Ratio of total charge density to ionic charge density in previous increment of ESP. Initialized to 20.0 to start procedure.

XS - Computed value of exponential argument in equation (2) for the estimated overall efficiency.

ETAPF - Computed estimated overall collection fraction per given length increment.

DW(I) - Computed estimated amount of material removed in a given length increment (kg/m^3).

QSAT(J) - Saturation charge on a given particle size (coul).

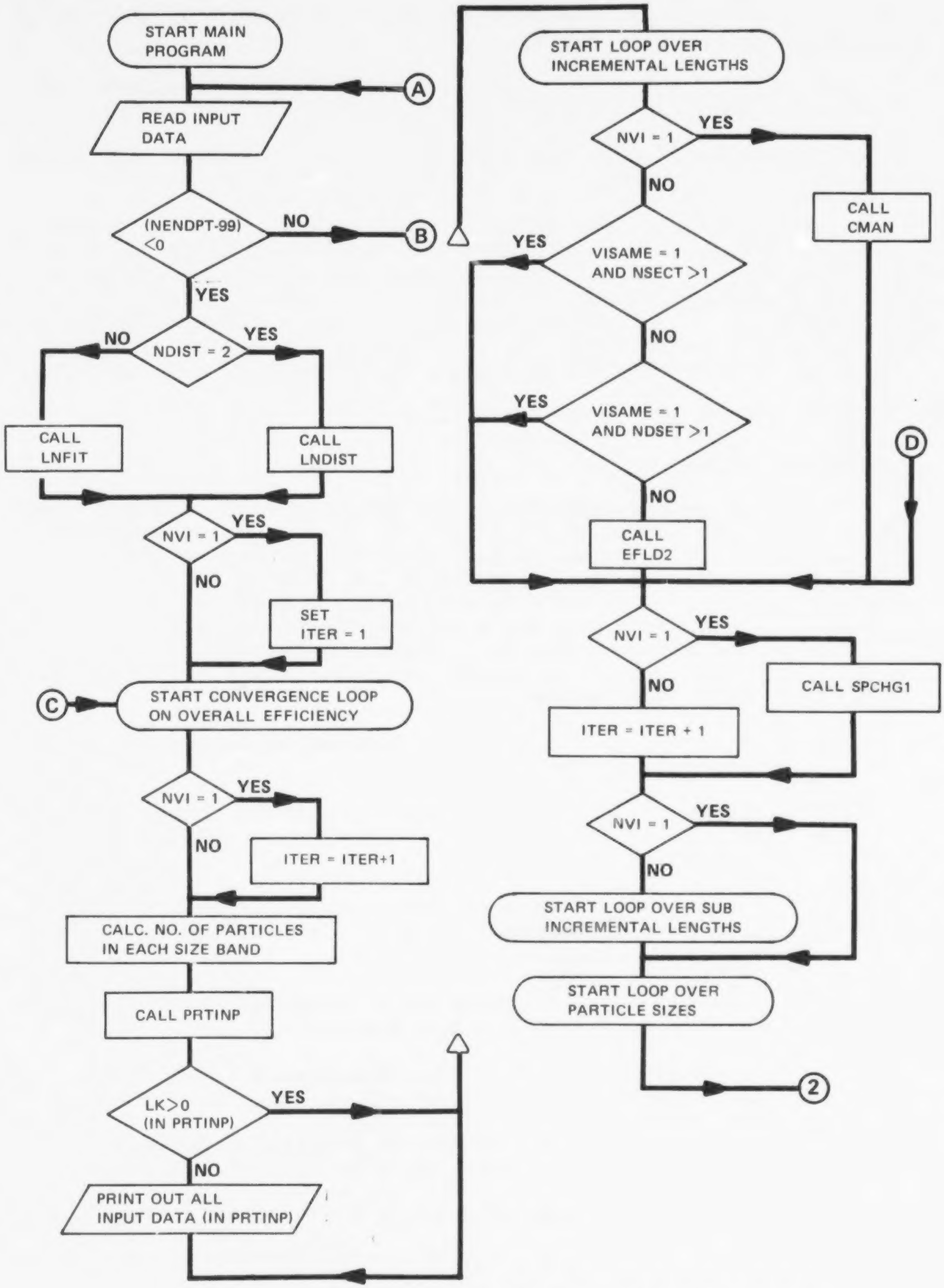

START MAIN PROGRAM
A
READ INPUT DATA
(NENDPT-99) <0
NO
B
YES
NDIST = 2
NO
YES
CALL LNFIT
CALL LNDIST
NVI = 1
YES
NO
SET ITER = 1
C
START CONVERGENCE LOOP ON OVERALL EFFICIENCY
NVI = 1
YES
NO
ITER = ITER+1
CALC. NO. OF PARTICLES IN EACH SIZE BAND
CALL PRTINP
LK>0 (IN PRTINP)
YES
NO
PRINT OUT ALL INPUT DATA (IN PRTINP)
START LOOP OVER INCREMENTAL LENGTHS
NVI = 1
YES
NO
CALL CMAN
VISAME = 1 AND NSECT >1
YES
NO
VISAME = 1 AND NDSET >1
YES
NO
D
CALL EFLD2
NVI = 1
YES
NO
CALL SPCHG1
ITER = ITER + 1
NVI = 1
YES
NO
START LOOP OVER SUB INCREMENTAL LENGTHS
START LOOP OVER PARTICLE SIZES
2

Figure 8. Simplified flow chart for the entire program (Sheet 1 of 4).

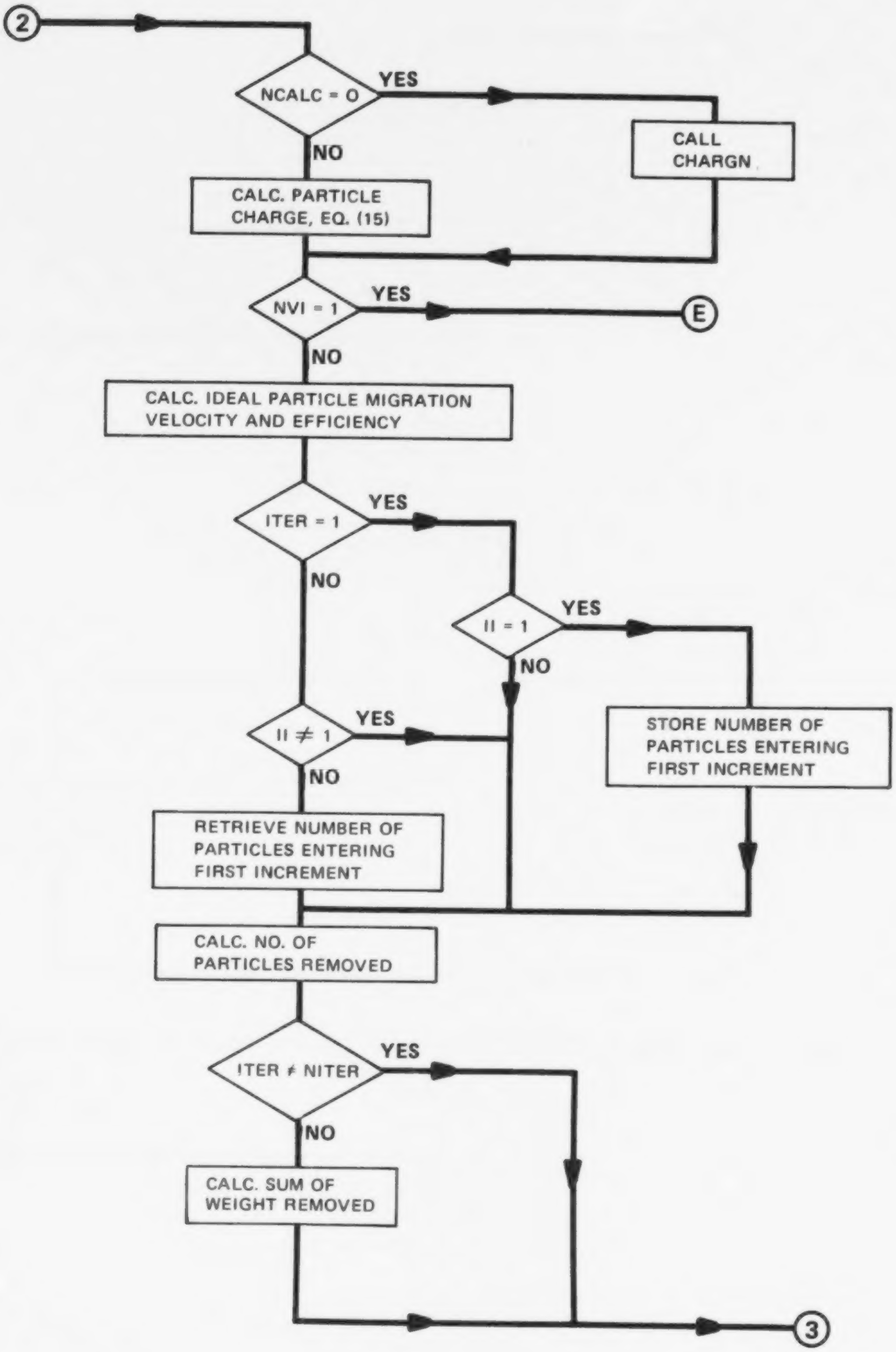

2
NCALC = O
YES
CALL CHARGN
NO
CALC. PARTICLE CHARGE, EQ. (15)
NVI = 1
YES
E
NO
CALC. IDEAL PARTICLE MIGRATION VELOCITY AND EFFICIENCY
ITER = 1
YES
NO
II = 1
YES
NO
STORE NUMBER OF PARTICLES ENTERING FIRST INCREMENT
II ≠ 1
YES
NO
RETRIEVE NUMBER OF PARTICLES ENTERING FIRST INCREMENT
CALC. NO. OF PARTICLES REMOVED
ITER ≠ NITER
YES
NO
CALC. SUM OF WEIGHT REMOVED
3

Figure 8. Simplified flow chart for the entire program (Sheet 2 of 4).

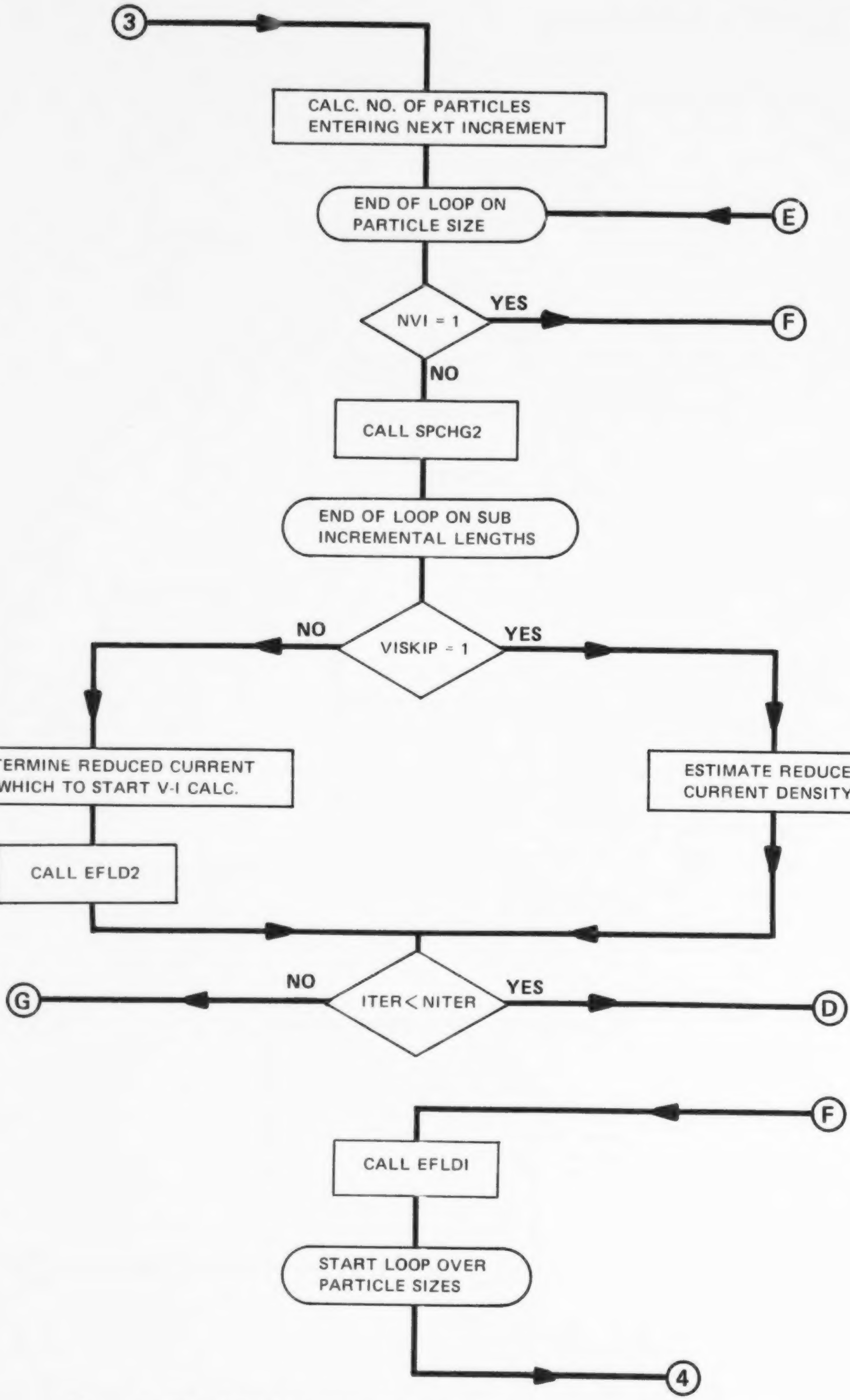

③
CALC. NO. OF PARTICLES ENTERING NEXT INCREMENT
END OF LOOP ON PARTICLE SIZE
E
NVI = 1
YES
F
NO
CALL SPCHG2
END OF LOOP ON SUB INCREMENTAL LENGTHS
VISKIP = 1
NO
YES
DETERMINE REDUCED CURRENT AT WHICH TO START V-I CALC.
ESTIMATE REDUCED CURRENT DENSITY
CALL EFLD2
ITER < NITER
NO
YES
G
D
F
CALL EFLDI
START LOOP OVER PARTICLE SIZES
④

Figure 8. Simplified flow chart for the entire program (Sheet 3 of 4).

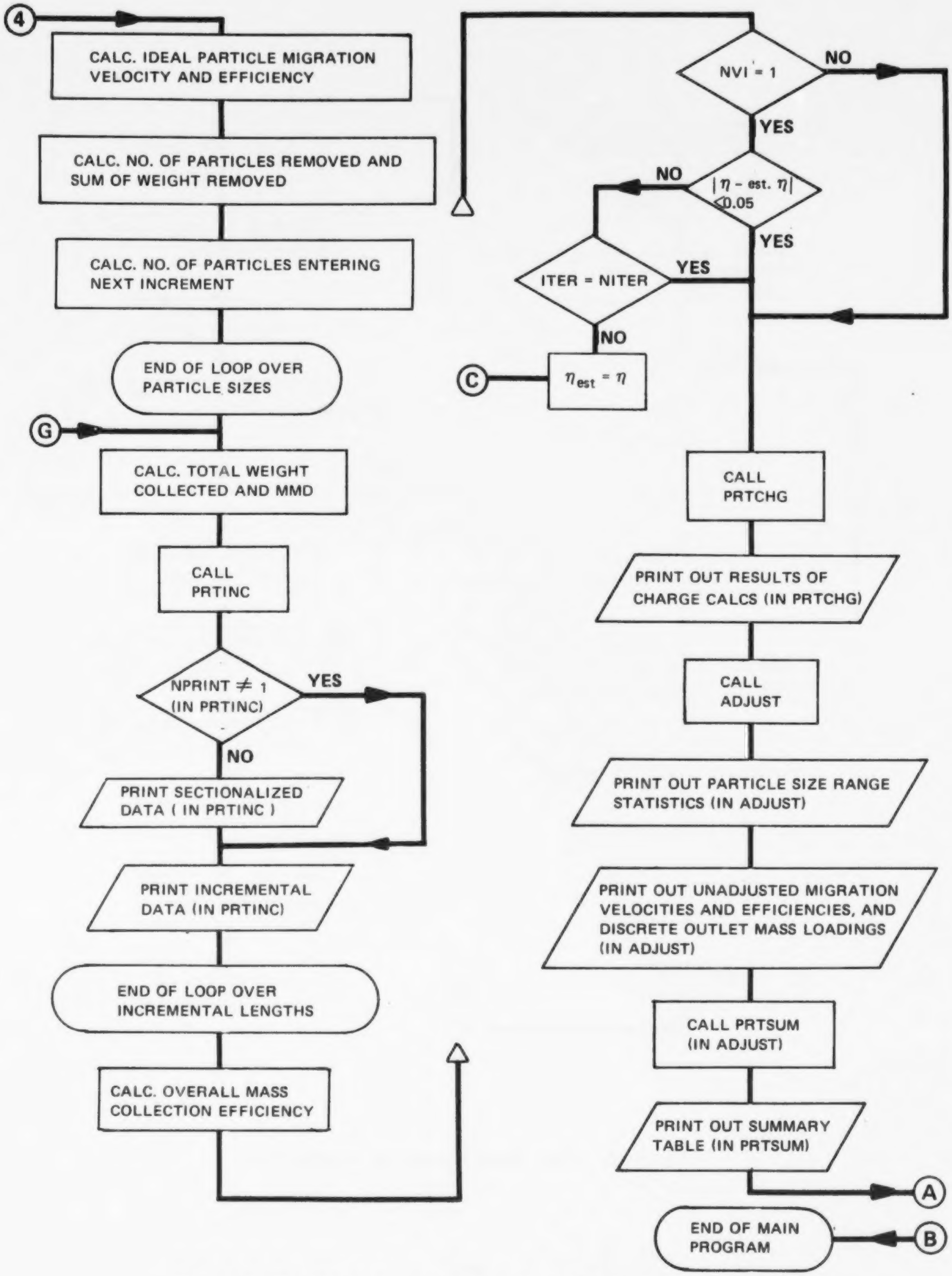

4
CALC. IDEAL PARTICLE MIGRATION VELOCITY AND EFFICIENCY
CALC. NO. OF PARTICLES REMOVED AND SUM OF WEIGHT REMOVED
CALC. NO. OF PARTICLES ENTERING NEXT INCREMENT
END OF LOOP OVER PARTICLE SIZES
G
CALC. TOTAL WEIGHT COLLECTED AND MMD
CALL PRTINC
NPRINT ≠ 1 (IN PRTINC)
YES
NO
PRINT SECTIONALIZED DATA (IN PRTINC)
PRINT INCREMENTAL DATA (IN PRTINC)
END OF LOOP OVER INCREMENTAL LENGTHS
CALC. OVERALL MASS COLLECTION EFFICIENCY
NVI = 1
NO
YES
|η - est. η| <0.05
NO
YES
ITER = NITER
YES
NO
C
η_est = η
CALL PRTCHG
PRINT OUT RESULTS OF CHARGE CALCS (IN PRTCHG)
CALL ADJUST
PRINT OUT PARTICLE SIZE RANGE STATISTICS (IN ADJUST)
PRINT OUT UNADJUSTED MIGRATION VELOCITIES AND EFFICIENCIES, AND DISCRETE OUTLET MASS LOADINGS (IN ADJUST)
CALL PRTSUM (IN ADJUST)
PRINT OUT SUMMARY TABLE (IN PRTSUM)
A
END OF MAIN PROGRAM
B

Figure 8. Simplified flow chart for the entire program (Sheet 4 of 4).

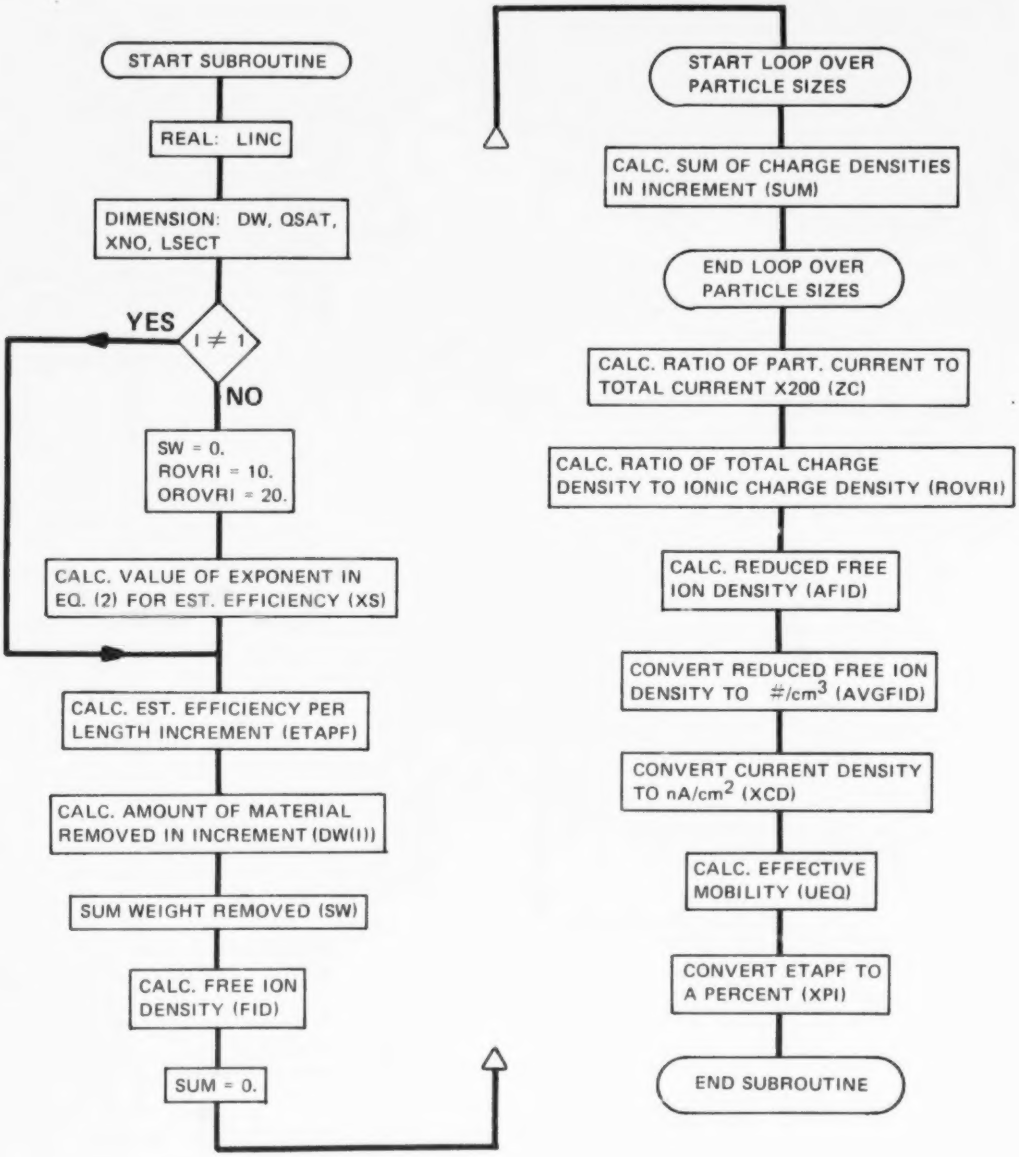

START SUBROUTINE
REAL: LINC
DIMENSION: DW, QSAT, XNO, LSECT
YES
I ≠ 1
NO
SW = 0.
ROVRI = 10.
OROVRI = 20.
CALC. VALUE OF EXPONENT IN EQ. (2) FOR EST. EFFICIENCY (XS)
CALC. EST. EFFICIENCY PER LENGTH INCREMENT (ETAPF)
CALC. AMOUNT OF MATERIAL REMOVED IN INCREMENT (DW(I))
SUM WEIGHT REMOVED (SW)
CALC. FREE ION DENSITY (FID)
SUM = 0.
START LOOP OVER PARTICLE SIZES
CALC. SUM OF CHARGE DENSITIES IN INCREMENT (SUM)
END LOOP OVER PARTICLE SIZES
CALC. RATIO OF PART. CURRENT TO TOTAL CURRENT X200 (ZC)
CALC. RATIO OF TOTAL CHARGE DENSITY TO IONIC CHARGE DENSITY (ROVRI)
CALC. REDUCED FREE ION DENSITY (AFID)
CONVERT REDUCED FREE ION DENSITY TO #/cm3 (AVGFID)
CONVERT CURRENT DENSITY TO nA/cm2 (XCD)
CALC. EFFECTIVE MOBILITY (UEQ)
CONVERT ETAPF TO A PERCENT (XPI)
END SUBROUTINE

Figure 9. Flow chart for subroutine SPCHG1.

XNO(J) - Number of particles per unit volume of gas of a given particle size entering a given length increment ($\#/m^3$).

W - Weight of material per unit time (mass flux) in a given length increment (kg/sec).

LSECT(K) - Number of length increments in a given electrical section.

TC - Total current in a given electrical section (A).

VG - Gas volume flow rate in a given electrical section (m^3/sec).

ETAO - Estimated overall mass efficiency of ESP (%).

FID - Computed free ion density in a given electrical section ($\#/m^3$).

AFID - Computed reduced free ion density for particle charging in a given electrical section ($\#/m^3$).

AVGFID - Reduced free ion density ($\#/cm^3$).

XCD - Average current density at the plate in a given electrical section (nA/cm^2).

U - Ion mobility in a given electrical section ($m^2/V\text{-}sec$).

UEQ - Effective charge carrier mobility in a given length increment ($m^2/V\text{-}sec$). Restricted to a lower limit of 1×10^{-4} $m^2/V\text{-}sec$ in main program to avoid convergence difficulties when used in subroutine EFLD1.

I - Index specifying the given length increment. Can not exceed a value of 50.

NSECT - Indicator specifying the given electrical section of the ESP. Can not exceed a value of 10.

LINC - Length of each increment in a given electrical section (m).

PL - Total electrical length of ESP (m).

CD - Average current density at the plate in a given electrical section (A/m^2).

E - Electronic charge (coul).

ERAVG - Average electric field between the wire and plate (V/m).

NS - Number of particle size bands in size distribution histogram. Can not exceed a value of 20.

XPI - Computed estimated overall collection efficiency per given length increment (%).

Of the above variables, the values of the following must be provided by the main program: QSAT(J), XNO(J), W, LSECT(K), TC, VG, ETAO, U, I, NSECT, LINC, PL, CD, E, ERAVG, and NS. The values of the following variables are determined in the subroutine: SW, ROVRI, OROVRI, XS, ETAPF, DW, FID, AFID, AVGFID, XCD, UEQ, and XPI. In the above arrays, I, J, and K can not exceed 45, 20, and 10, respectively. The restrictions on I, J, and K limit the number of length increments, the number of particle size bands, and the number of electrical sections, respectively.

Subroutine SPCHG2

This subroutine determines the effect of "particulate space charge" in each subincrement of length by using the new procedure discussed earlier in this report and in Appendix A to calculate an "effective" charge carrier mobility. Figure 10 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program and this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

NS - Number of particle size bands in size distribution histogram. Can not exceed a value of 20.

XNO(J) - Number of particles per unit volume of gas of a given particle size entering a given length increment (#/m^3).

VIS - Gas viscosity in a given electrical section (kg/m-sec).

RAD(J) - Radius of a given particle size (m).

LINC - Length of each increment in a given electrical section (m).

E - Electronic charge (coul).

U - Ion mobility in a given electrical section (m^2/V-sec).

ERAVG - Average electric field between the wire and plate (V/m).

DNSION - Ion density in the absence of particles (#/m^3).

DELTNP - Number density of charges transferred from ions to particles in a given subincrement of length (#/m^3).

SUMMOB - Weighted summation of particle mobilities (m^2/V-sec/m^3).

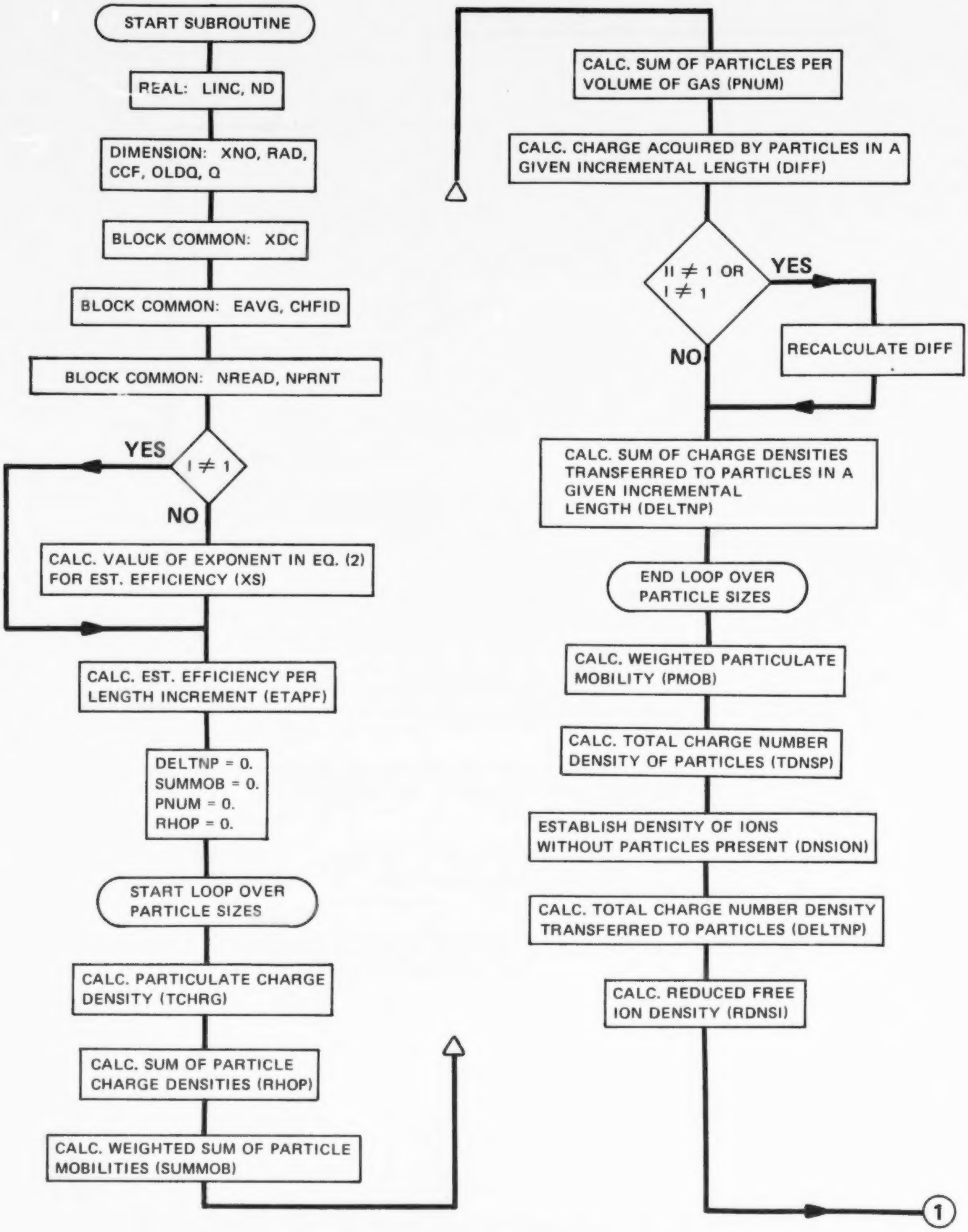

START SUBROUTINE
REAL: LINC, ND
DIMENSION: XNO, RAD, CCF, OLDQ, Q
BLOCK COMMON: XDC
BLOCK COMMON: EAVG, CHFID
BLOCK COMMON: NREAD, NPRNT
I ≠ 1
YES
NO
CALC. VALUE OF EXPONENT IN EQ. (2) FOR EST. EFFICIENCY (XS)
CALC. EST. EFFICIENCY PER LENGTH INCREMENT (ETAPF)
DELTNP = 0.
SUMMOB = 0.
PNUM = 0.
RHOP = 0.
START LOOP OVER PARTICLE SIZES
CALC. PARTICULATE CHARGE DENSITY (TCHRG)
CALC. SUM OF PARTICLE CHARGE DENSITIES (RHOP)
CALC. WEIGHTED SUM OF PARTICLE MOBILITIES (SUMMOB)
CALC. SUM OF PARTICLES PER VOLUME OF GAS (PNUM)
CALC. CHARGE ACQUIRED BY PARTICLES IN A GIVEN INCREMENTAL LENGTH (DIFF)
II ≠ 1 OR I ≠ 1
YES
NO
RECALCULATE DIFF
CALC. SUM OF CHARGE DENSITIES TRANSFERRED TO PARTICLES IN A GIVEN INCREMENTAL LENGTH (DELTNP)
END LOOP OVER PARTICLE SIZES
CALC. WEIGHTED PARTICULATE MOBILITY (PMOB)
CALC. TOTAL CHARGE NUMBER DENSITY OF PARTICLES (TDNSP)
ESTABLISH DENSITY OF IONS WITHOUT PARTICLES PRESENT (DNSION)
CALC. TOTAL CHARGE NUMBER DENSITY TRANSFERRED TO PARTICLES (DELTNP)
CALC. REDUCED FREE ION DENSITY (RDNSI)
①

Figure 10. Flow chart for subroutine SPCHG2 (Sheet 1 of 2).

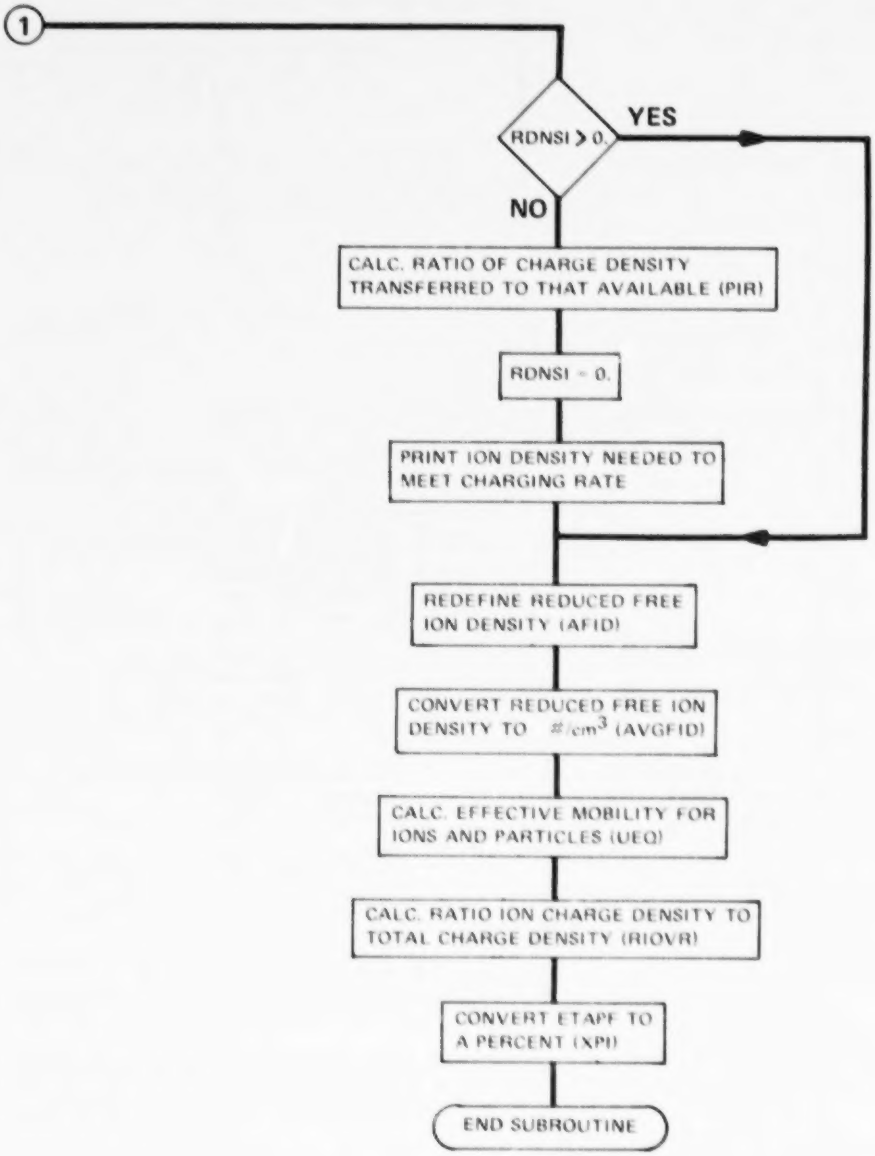

1
RDNSI > 0.
YES
NO
CALC. RATIO OF CHARGE DENSITY TRANSFERRED TO THAT AVAILABLE (PIR)
RDNSI = 0.
PRINT ION DENSITY NEEDED TO MEET CHARGING RATE
REDEFINE REDUCED FREE ION DENSITY (AFID)
CONVERT REDUCED FREE ION DENSITY TO #/cm³ (AVGFID)
CALC. EFFECTIVE MOBILITY FOR IONS AND PARTICLES (UEQ)
CALC. RATIO ION CHARGE DENSITY TO TOTAL CHARGE DENSITY (RIOVR)
CONVERT ETAPF TO A PERCENT (XPI)
END SUBROUTINE

Figure 10. Flow chart for subroutine SPCHG2 (Sheet 2 of 2).

PNUM - Total number of particles per unit volume of gas entering a given subincrement of length (#/m^3).

RHOP - Total average particulate charge density in a given subincrement of length (coul/m^3).

TCHRG - Average particle charge density for a given particle size in a given subincrement of length (coul/m^3).

PMOB - Weighted particulate mobility in a given subincrement of length (m^2/V-sec).

TDNSP - Total average particulate charge number density in a given subincrement of length (#/m^3).

RDNSI, AFID - Average reduced ion density in a given subincrement of length (#/m^3).

UEQ - Effective charge carrier mobility in a given subincrement of length (m^2/V-sec).

AVGFID - Average reduced ion density in a given subincrement of length (#/cm^3).

RIOVR - Ratio of ionic charge density to total charge density in a given subincrement of length.

I - Index specifying the given length increment. Can not exceed a value of 45.

XS - Computed value of exponential argument in equation (2) for the design overall efficiency.

ETAO - Design overall mass efficiency of ESP (%).

PL - Total electrical length of ESP (m).

ETAPF - Computed design overall collection fraction per given length increment.

CCF(J) - Cunningham slip correction factor for a given particle size.

XPI - Computed design overall collection efficiency per given length increment (%).

OLDQ(J) - Value of charge for a given particle size acquired through all subincrements of length up to the subincrement under consideration (coul).

Q(J) - Value of charge for a given particle size acquired through the subincrement of length under consideration (coul).

II - Index specifying the given subincrement of length. Can not exceed a value of 30.

NSECT - Indicator specifying the given electrical section of the ESP. Can not exceed a value of 10.

The following is a list of the necessary variables which are in common with the main program.

XDC(I,J) - Charge on a given particle size at the end of a given length increment (coul).

EAVG(K) - Average electric field in a given subincrement of length (V/m).

CHRID(K) - Average ion density in the absence of particles in a given subincrement of length (#/m^3).

NPRNT - Indicator which specifies the logical unit number of the printer.

Of the above variables, the values of the following must be provided by the main program: NS, XNO, VIS, RAD, LINC, E, U, ERAVG, I, ETAO, PL, CCF, OLDQ, Q, II, ND, NSECT, XDC, EAVG, CHFID, and NPRNT. The values of the following variables are determined in the subroutine: DNSION, DELTNP, SUMMOB, PNUM, RHOP, TCHRG, PMOB, TDNSP, RDNSI, AFID, UEQ, AVGFID, RIOVR, XS, ETAPF, and XPI. In the above arrays, I, J, and K can not exceed values of 45, 20, and 30, respectively. The restrictions on I, J, and K limit the number of length increments, the number of particle size bands, and the number of subincremental lengths in a given length increment, respectively. If, in a given subincrement of length, there are not enough free ions available to meet the charging rates of all the particle sizes, then the subroutine prints out a message which states the increase in ion density necessary to meet the charging rates. In this case, the free ion density is defined as zero and it is assumed that the charging rate was met.

Subroutine CMAN

This subroutine calculates an initial estimate of the electric potential at each point in a grid which is established in either EFLD1 or EFLD2 for the purpose of determining the electrical conditions in a wire-plate precipitator. The calculation is based on an electrostatic solution for a wire-plate geometry. Thus, this initial estimate does not include the effects of space charge. The equation which is used to calculate the initial values of electric potential at the grid points is given by[28]

$$V(x,y) = V_w \frac{\sum\limits_{m=-\infty}^{\infty} \ln \left[\dfrac{\cosh \pi(y-2mS_y)/2S_x - \cos(\pi x/2S_x)}{\cosh \pi(y-2mS_y)/2S_x + \cos(\pi x/2S_x)}\right]}{\sum\limits_{m=-\infty}^{\infty} \ln \left[\dfrac{\cosh(\pi m S_y/S_x) - \cos(\pi r_w/2S_x)}{\cosh(\pi m S_y/S_x) + \cos(\pi r_w/2S_x)}\right]}, \qquad (26)$$

where $V(x,y)$ = electrical potential (V),

V_w = applied voltage (V),

S_x = wire-to-plate spacing (m),

S_y = one half wire-to-wire spacing (m),

r_w = radius of corona wire (m),

x = coordinate position measured toward plate with the corona wire as origin (m), and

y = coordinate position measured parallel to plates with the corona wire as origin (m).

In practice the series converges rapidly and only a few terms need be evaluated. The sums in equation (26) are performed over the number of wires in a given gas passage of a given electrical section.

Figure 11 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program, other subroutines, and this subroutine is transferred through calling arguments and a block common statement. The following is a sequential list of the calling arguments and their descriptions.

VW - Electric potential at the wire (V).

NX - Number of grid points in the x-direction. Can not exceed a value of 15.

NY - Number of grid points in the y-direction. Can not exceed a value of 15.

SX - Wire-to-plate spacing (m).

SY - One-half wire-to-wire spacing (m).

PI - Value of the constant pi.

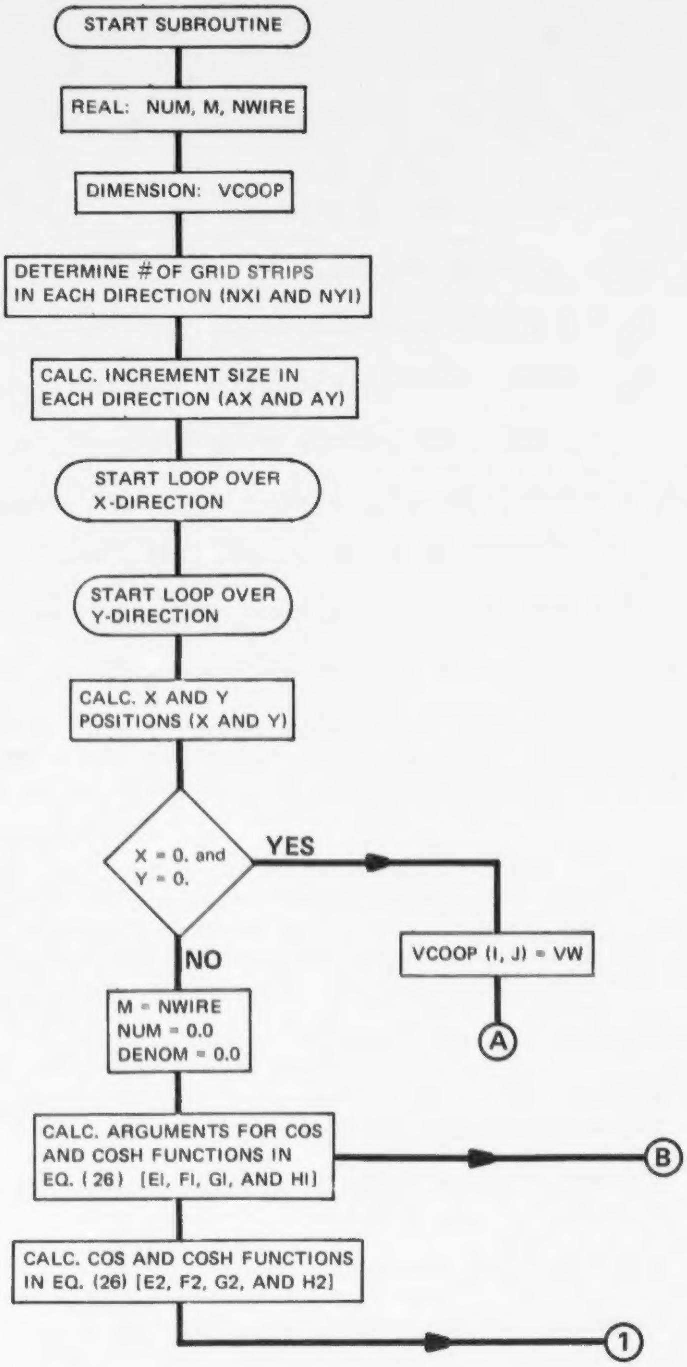

START SUBROUTINE
REAL: NUM, M, NWIRE
DIMENSION: VCOOP
DETERMINE # OF GRID STRIPS IN EACH DIRECTION (NXI AND NYI)
CALC. INCREMENT SIZE IN EACH DIRECTION (AX AND AY)
START LOOP OVER X-DIRECTION
START LOOP OVER Y-DIRECTION
CALC. X AND Y POSITIONS (X AND Y)
X = 0. and Y = 0.
YES
VCOOP (I, J) = VW
A
NO
M = NWIRE
NUM = 0.0
DENOM = 0.0
CALC. ARGUMENTS FOR COS AND COSH FUNCTIONS IN EQ. (26) [EI, FI, GI, AND HI]
B
CALC. COS AND COSH FUNCTIONS IN EQ. (26) [E2, F2, G2, AND H2]
1

Figure 11. Flow chart for subroutine CMAN (Sheet 1 of 2).

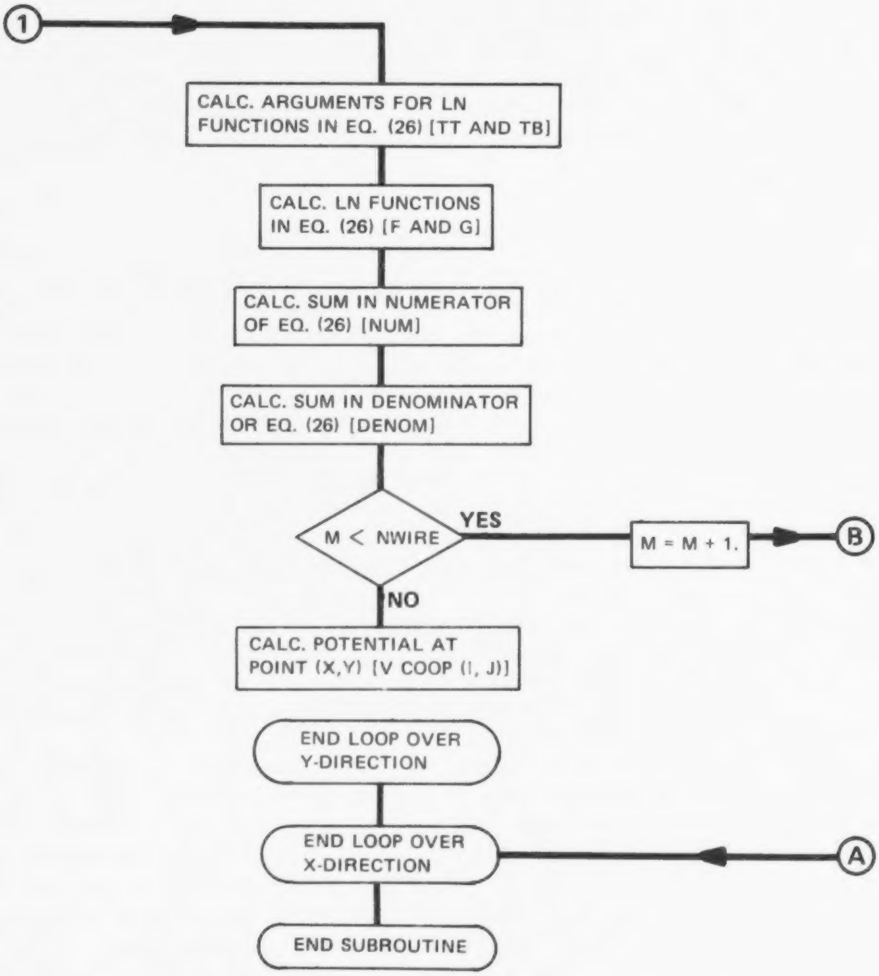

1
CALC. ARGUMENTS FOR LN FUNCTIONS IN EQ. (26) [TT AND TB]
CALC. LN FUNCTIONS IN EQ. (26) [F AND G]
CALC. SUM IN NUMERATOR OF EQ. (26) [NUM]
CALC. SUM IN DENOMINATOR OR EQ. (26) [DENOM]
M < NWIRE
YES
M = M + 1.
B
NO
CALC. POTENTIAL AT POINT (X,Y) [V COOP (I, J)]
END LOOP OVER Y-DIRECTION
END LOOP OVER X-DIRECTION
A
END SUBROUTINE

Figure 11. Flow chart for subroutine CMAN (Sheet 2 of 2).

AC - Radius of discharge electrode (m).

NWIRE - Number of wires per gas passage per electrical section.

The following variable is in common with the main program and subroutine EFLD2.

VCOOP(I,J) - Initial estimate of potential at points in the grid (V). I and J can not exceed a value of 15.

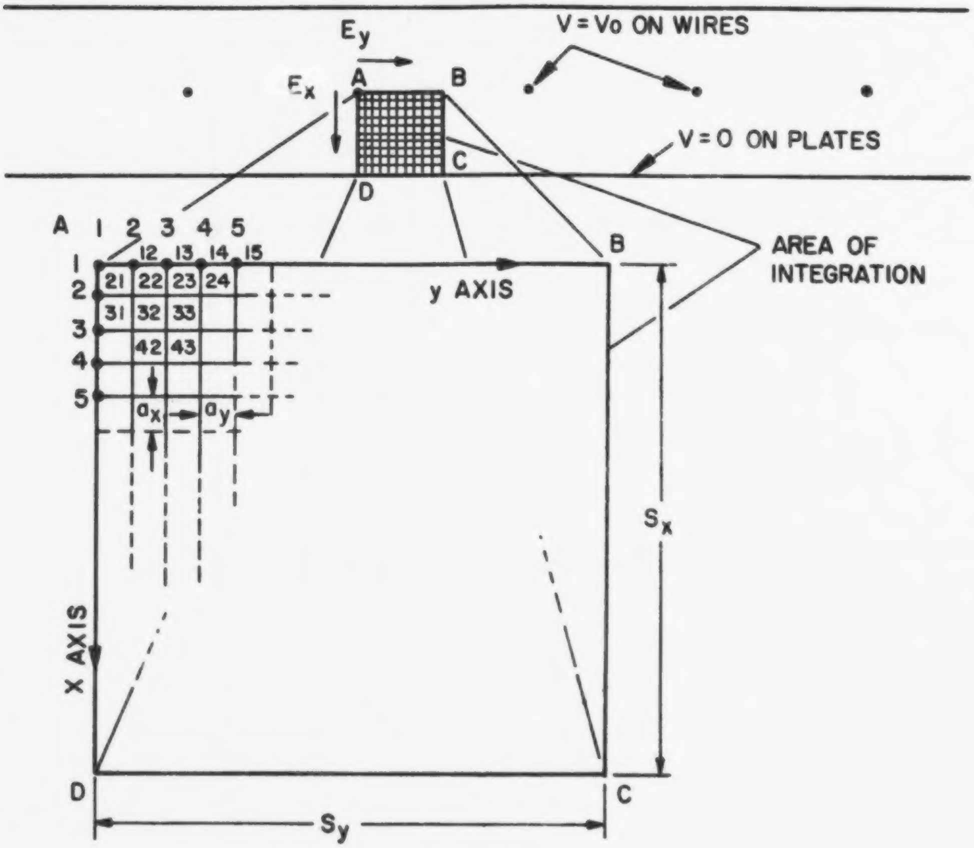
Of the above variables, the values of the following must be provided by the main program: VW, NX, NY, SX, SY, PI, AC, and NWIRE. VCOOP is determined in the subroutine. The restrictions on I and J limit the number of grid points in the x-direction and the number of grid points in the y-direction, respectively.

Subroutine EFLD1

This subroutine calculates the average electric field at the plate of a wire-plate precipitator. Its usage depends upon measured or known values of applied voltage and current. The electric field at the plate is found by solving equations (9) and (10) simultaneously and subject to the existing boundary conditions using a numerical relaxation technique.[29,30,31,32] In solving the equations, the corona zone surrounding the discharge wire is considered only as a source of ions and the high values of electric field intensity existing in this region are not treated in the calculation. The region outside the corona zone, where the values of electric field intensity are relatively low, is referred to as the space-charge zone and is assumed to contain unipolar ions.

Figure 12 shows the basic area of interest in the precipitator for which equations (9) and (10) are solved. Figure 12 also includes the geometry and nomenclature used in the numerical analysis. Due to the symmetry of the problem it is necessary to integrate only over the rectangle shown in Figure 12 and then assert that the solutions hold for all similar rectangles within the duct. In this manner the entire two-dimensional area can be taken into account. In the actual numerical procedure, occasions occur when values of V, E, and ρ from positions outside the rectangle are used. In this case it is justified to assign to the functions V, E, and ρ the same values they had at symmetrically located points within the area of the rectangle. This is necessary in order for the integration to include values of V and ρ which exist on the boundaries in such a way that they converge toward an exact solution along with the interior points.

In order to employ the numerical technique, the area of interest is divided into a fine rectangular grid as shown in Figure 13. Point "0" is the point of interest for the following discussion. However, once V_0, E_0, and ρ_0 are calculated here, the label "0" is moved to a neighboring point and the calculation


E_y
V = Vo ON WIRES
E_x
A
B
V = 0 ON PLATES
C
D
A
1 2 3 4 5
12 13 14 15
21 22 23 24
31 32 33
42 43
1
2
3
4
5
a_x
a_y
B
y AXIS
AREA OF INTEGRATION
S_x
X AXIS
D
C
S_y

S_y = ONE HALF WIRE TO WIRE SPACING

S_x = WIRE TO PLATE SPACING

$a_x\ a_y$ = **INCREMENT SIZES FOR INTEGRATION**

V_0 = APPLIED VOLTAGE

E_x = COMPONENT OF ELECTRIC FIELD PERPENDICULAR TO PLATE

E_y = LONGITUDINAL COMPONENT OF ELECTRIC FIELD

j = AVERAGE CURRENT DENSITY

Figure 12. Nomenclature used in the numerical analysis of the electrical conditions in wire-plate precipitators.

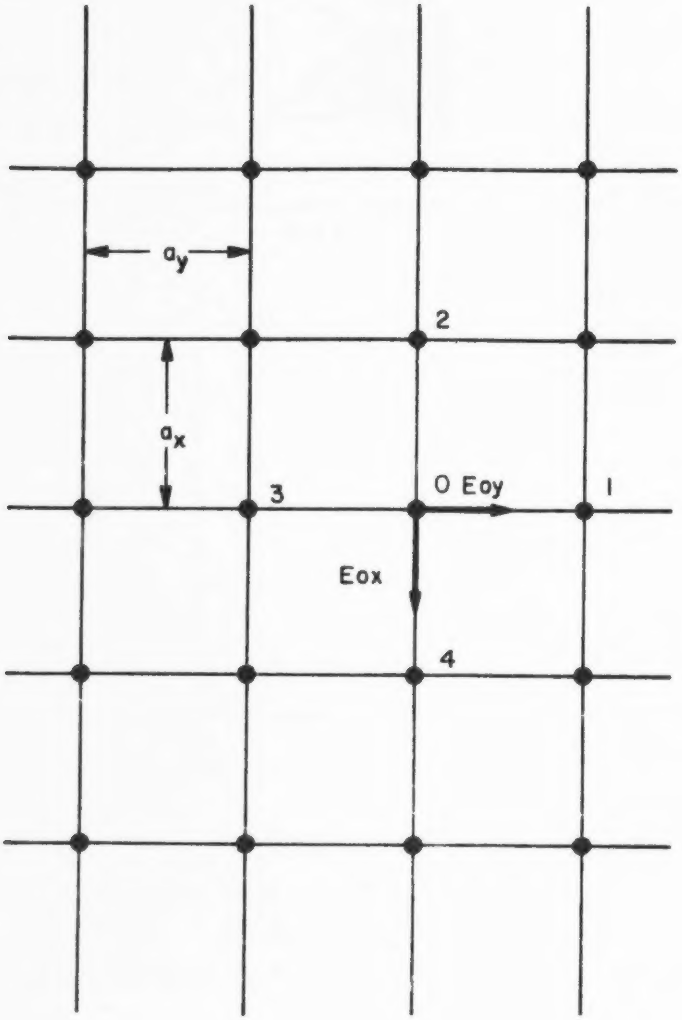

a_y
a_x
2
3
O Eoy
1
Eox
4

Figure 13. Partial grid showing nomenclature used in the numerical analysis of the electrical conditions.

repeated. Each point in the grid would eventually become point "0".

From Figure 13,

$$\frac{\Delta V_0}{\Delta x} = \frac{1}{2a_x} (V_4 - V_2),$$

$$\frac{\Delta V_0}{\Delta y} = \frac{1}{2a_y} (V_1 - V_3),$$

$$\frac{\Delta^2 V_0}{\Delta x^2} = \frac{V_4+V_2-2V_0}{a_x^2} \quad , \tag{27}$$

and

$$\frac{\Delta^2 V_0}{\Delta y^2} = \frac{V_3+V_1-2V_0}{a_y^2} \tag{28}$$

Equations (27) and (28) can be used in equation (9) and the resulting equation can be solved for V_0 to give

$$V_0 \simeq \frac{1}{2(a_x^2+a_y^2)} \left[a_y^2(V_2+V_4) + a_x^2(V_1+V_3) + \frac{a_x^2 a_y^2 \rho_0}{\varepsilon_0}\right]. \tag{29}$$

Again, from Figure 13,

$$\frac{\Delta \rho_0}{\Delta x} = \frac{\rho_0-\rho_2}{a_x} \quad , \tag{30}$$

$$\frac{\Delta \rho_0}{\Delta y} = \frac{\rho_0-\rho_3}{a_y} \quad , \tag{31}$$

$$\frac{\Delta b_0}{\Delta x} = \frac{b_0-b_2}{a_x} \quad , \tag{32}$$

and

$$\frac{\Delta b_0}{\Delta y} = \frac{b_0-b_3}{a_y} \quad . \tag{33}$$

Equations (30)-(33) can be used in equation (10) and the resulting equation can be solved for ρ_0 to given

$$\rho_0 = -\alpha \pm \sqrt{\alpha^2+\beta} \quad , \tag{34}$$

where

$$\alpha = \frac{\varepsilon_0(2a_y b_0 E_{0x} + 2a_x b_0 E_{0y} - a_y b_2 E_{0x} - a_x b_3 E_{0y})}{2a_x a_y b_0} \quad ,$$

and

$$\beta = \frac{\varepsilon_0(a_y E_{0x}\rho_2 + a_x E_{0y}\rho_3)}{a_x a_y} \quad .$$

In subroutine EFLD1, solutions to equations (29) and (34) are obtained subject to the following boundary conditions:

(a) $V = V_w$ (applied voltage) at the wire;

(b) J_p = known or measured average current density at the plate;

(c) $V = 0$ on the plate (along line CD);

(d) $E_x = -\frac{\Delta V}{\Delta X} = 0$ and $E_y = -\frac{\Delta V}{\Delta Y} = 0$ at points A and B;

(e) $E_x = -\frac{\Delta V}{\Delta X} = 0$ along line AB;

(f) $E_y = -\frac{\Delta V}{\Delta Y} = 0$ along lines BC, CD, and AD.

The boundary conditions greatly simplify equation (34) along the lines AB, BC, AD, and CD and, in fact, make the calculation of simultaneous solutions to equations (29) and (34) possible. Along the lines AB, BC, AD, and CD, α and β reduce to the following expressions:

$$\alpha_{AB} = \frac{\varepsilon_0(2a_x b_0 E_{0y} - a_x b_3 E_{0y})}{2a_x a_y b_0} \quad , \qquad (35)$$

$$\alpha_{BC} = \alpha_{AD} = \alpha_{CD} = \frac{\varepsilon_0(2a_y b_0 E_{0x} - a_y b_2 E_{0x})}{2a_x a_y b_0} \quad , \qquad (36)$$

$$\beta_{AB} = \frac{\varepsilon_0 E_{0y}\rho_3}{a_y} \quad , \qquad (37)$$

and

$$\beta_{BC} = \beta_{AD} = \beta_{CD} = \frac{\varepsilon_0 E_{0x}\rho_2}{a_x} \quad . \qquad (38)$$

In order to initiate the numerical procedure which finds the simultaneous solutions to equations (29) and (34), it is necessary to make initial estimates of the values of the electric potential at all grid points and the space charge density for the corona region. The initial values of electric potential are estimated using equation (26) which is evaluated in subroutine CMAN. An initial estimate of the space charge density near the discharge electrode is obtained by assuming that the corona region is cylindrical and using continuity of current. This initial estimate is calculated from the expression

$$\rho_s = \frac{2\ S_y J_P}{\pi b_s r_w f\ (30\delta + 9\sqrt{\delta/r_w})} \times 10^{-3}\ , \qquad (39)$$

where ρ_s = space charge density at the outer boundary of the ionized sheath (coul/m^3),

S_y = one-half wire-to-wire spacing (m),

J_p = average current density at the plate (A/m^2),

b_s = effective charge carrier mobility at the outer boundary of the ionized sheath (m^2/V-sec),

r_w = radius of the wire (cm),

f = roughness factor, and

δ = relative density of the gas.

The numerical procedure for finding the solutions to equations (29) and (34) consists of the following steps.

1. V is computed at every point in the integration grid using equation (26).

2. ρ is computed at every point in the integration grid from equations (34) and (39).

3. V is recomputed at every point in the integration grid using equation (29).

4. Steps 2 and 3 are repeated alternately until convergence occurs. Convergence on the potential grid is obtained when the value of the potential at each point in the grid is within one volt of the value calculated at that point in the previous iteration.

5. The computed current density (obtained using the relationship $J = -\rho \left(\frac{\Delta V}{\Delta x}\right) b$) is compared with the measured current density. If the computed and measured current densities do not agree within .1%, then the space charge representing the corona region is adjusted and steps 1 through 5 are repeated until agreement is obtained.

This procedure iterates on a grid of electric field and space charge density until convergence is obtained. The major approximation, and one that is seemingly unavoidable in practice, is the assumption that the motion of all charge carriers can, on the average, be described by a single effective mobility. The space charge introduced by the particulate present in flue gas would reduce the effective mobility. The procedure uses a reduced mobility which is calculated from equation (16) and is evaluated in subroutine SPCHG1. The reduction in mobility is limited to a value of 1×10^{-4} m^2/V-sec in order to prevent nonconvergence of the grid under certain conditions.

Figure 14 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program and this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

UEQ - Effective charge carrier mobility (m^2/V-sec). Limited to a lower value of 1×10^{-4} m^2/V-sec.

CD - Average current density at the plate (A/m^2).

AC - Radius of discharge electrode (m).

VO - Electric potential at the wire (V).

SX - Wire-to-plate spacing (m).

SY - One-half wire-to-wire spacing (m).

NX - Number of grid points in the x-direction. Can not exceed a value of 15.

NY - Number of grid points in the y-direction. Can not exceed a value of 15.

TDK - Temperature of the gas (°K).

P - Pressure of the gas (atm).

AEPLT - Average electric field at the plate (V/m).

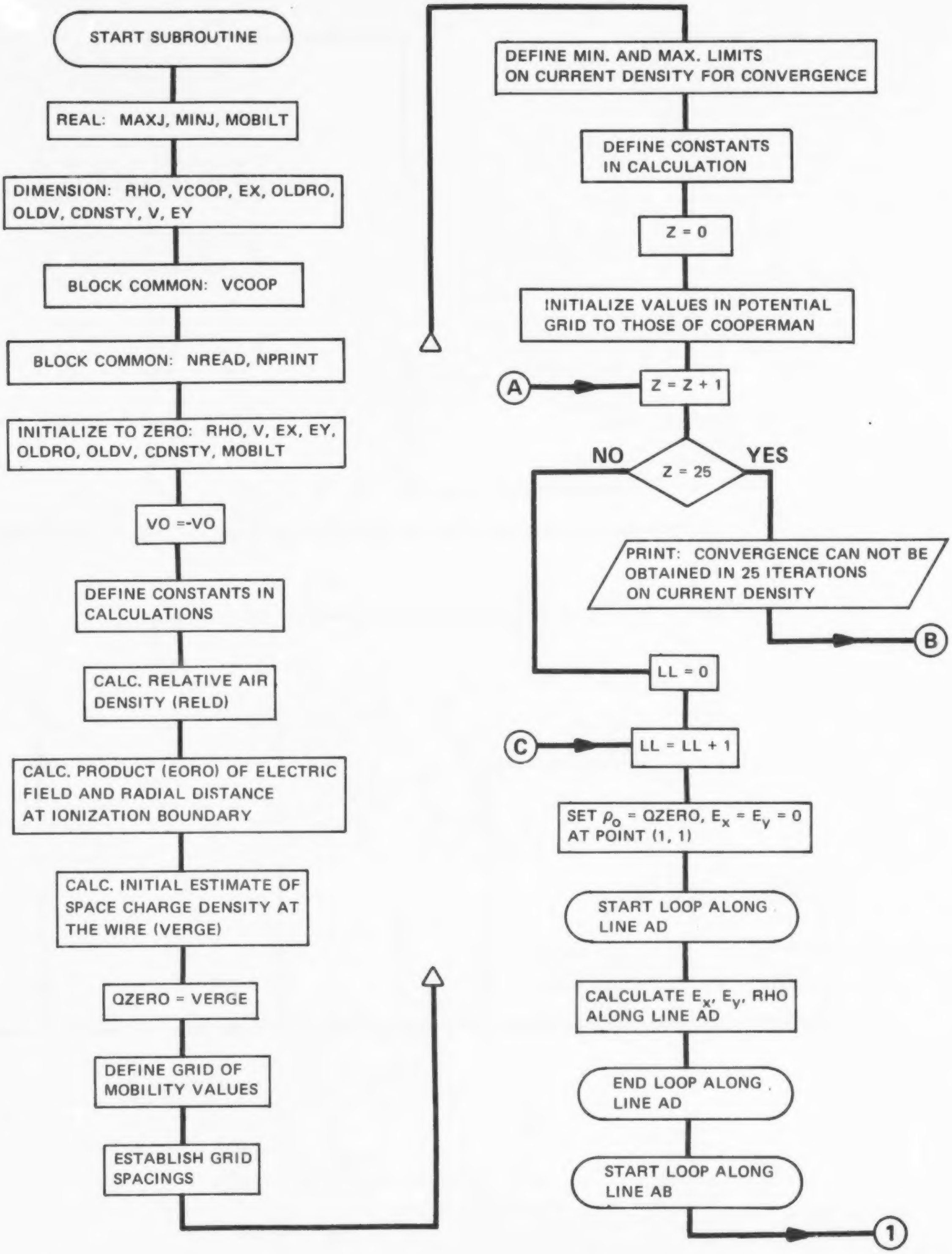

START SUBROUTINE
REAL: MAXJ, MINJ, MOBILT
DIMENSION: RHO, VCOOP, EX, OLDRO, OLDV, CDNSTY, V, EY
BLOCK COMMON: VCOOP
BLOCK COMMON: NREAD, NPRINT
INITIALIZE TO ZERO: RHO, V, EX, EY, OLDRO, OLDV, CDNSTY, MOBILT
VO =-VO
DEFINE CONSTANTS IN CALCULATIONS
CALC. RELATIVE AIR DENSITY (RELD)
CALC. PRODUCT (EORO) OF ELECTRIC FIELD AND RADIAL DISTANCE AT IONIZATION BOUNDARY
CALC. INITIAL ESTIMATE OF SPACE CHARGE DENSITY AT THE WIRE (VERGE)
QZERO = VERGE
DEFINE GRID OF MOBILITY VALUES
ESTABLISH GRID SPACINGS
DEFINE MIN. AND MAX. LIMITS ON CURRENT DENSITY FOR CONVERGENCE
DEFINE CONSTANTS IN CALCULATION
Z = 0
INITIALIZE VALUES IN POTENTIAL GRID TO THOSE OF COOPERMAN
A
Z = Z + 1
NO
Z = 25
YES
PRINT: CONVERGENCE CAN NOT BE OBTAINED IN 25 ITERATIONS ON CURRENT DENSITY
B
LL = 0
C
LL = LL + 1
SET ρ_o = QZERO, $E_x = E_y = 0$ AT POINT (1, 1)
START LOOP ALONG LINE AD
CALCULATE E_x, E_y, RHO ALONG LINE AD
END LOOP ALONG LINE AD
START LOOP ALONG LINE AB
1

Figure 14. Flow chart for subroutine EFLD1 (Sheet 1 of 3).

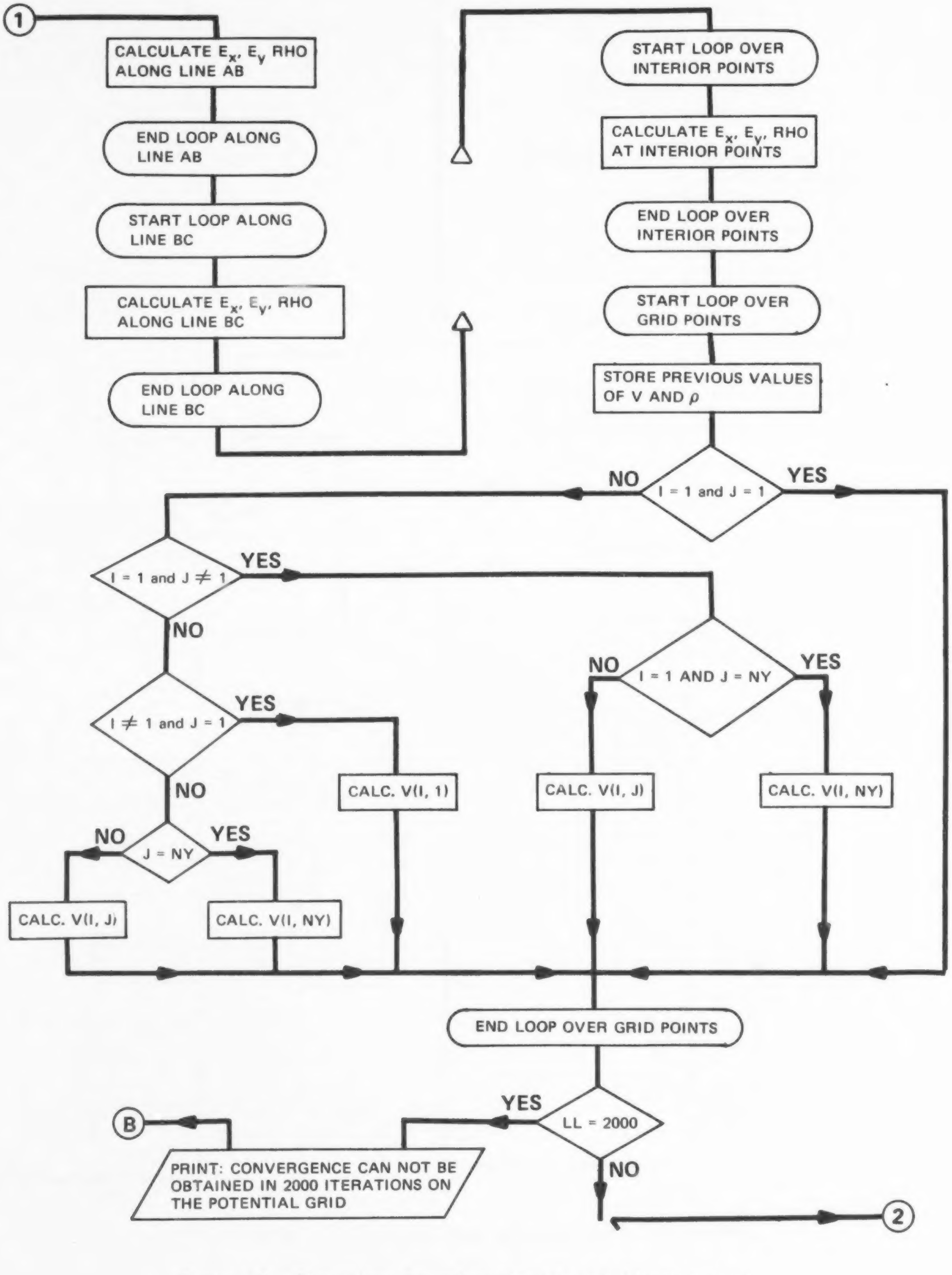
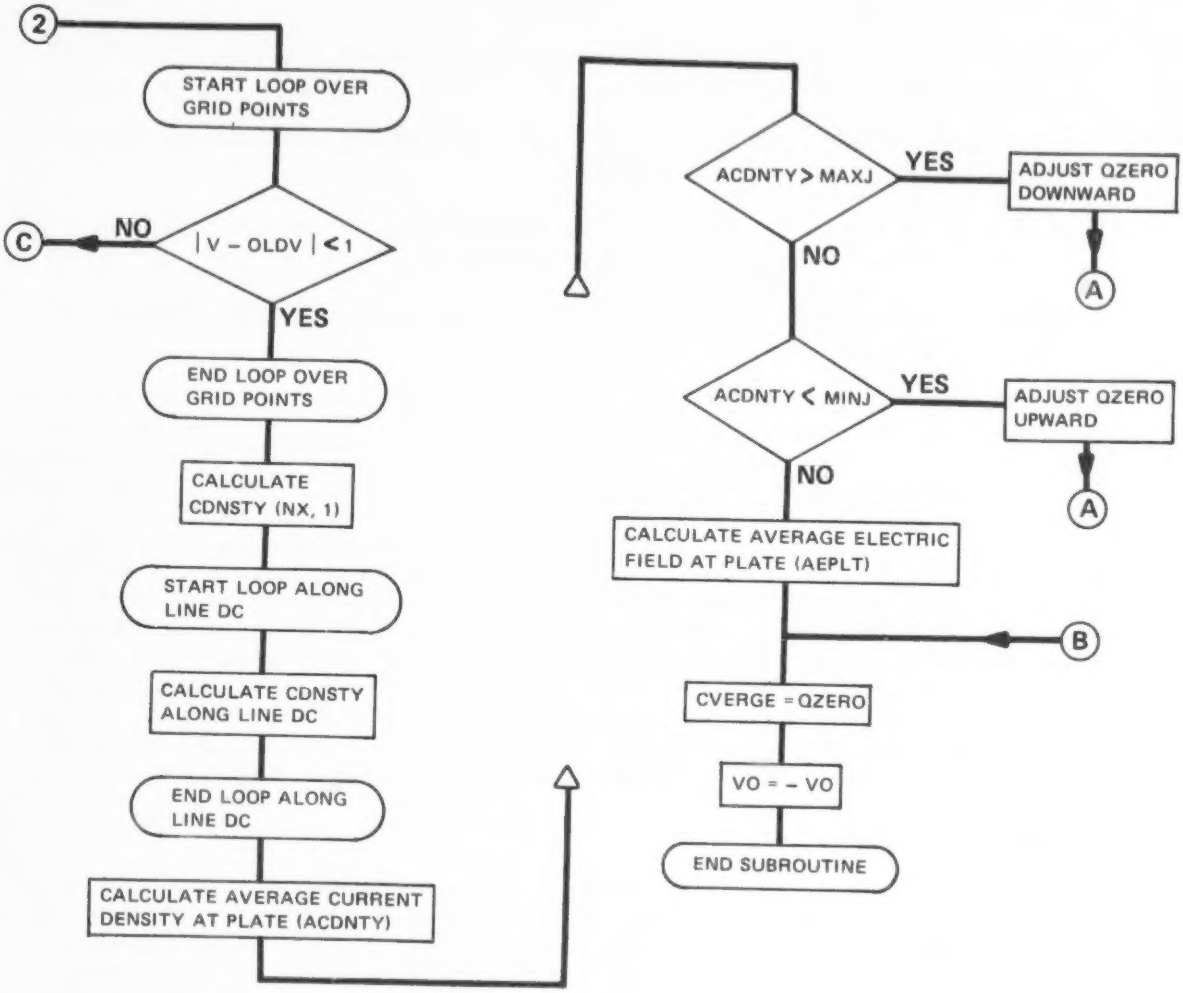

①
CALCULATE E_x, E_y RHO ALONG LINE AB
END LOOP ALONG LINE AB
START LOOP ALONG LINE BC
CALCULATE E_x, E_y, RHO ALONG LINE BC
END LOOP ALONG LINE BC
START LOOP OVER INTERIOR POINTS
CALCULATE E_x, E_y, RHO AT INTERIOR POINTS
END LOOP OVER INTERIOR POINTS
START LOOP OVER GRID POINTS
STORE PREVIOUS VALUES OF V AND ρ
NO
I = 1 and J = 1
YES
I = 1 and J ≠ 1
YES
NO
I = 1 AND J = NY
NO
YES
I ≠ 1 and J = 1
YES
NO
CALC. V(I, 1)
CALC. V(I, J)
CALC. V(I, NY)
NO
J = NY
YES
CALC. V(I, J)
CALC. V(I, NY)
END LOOP OVER GRID POINTS
YES
LL = 2000
NO
Ⓑ
PRINT: CONVERGENCE CAN NOT BE OBTAINED IN 2000 ITERATIONS ON THE POTENTIAL GRID
②

Figure 14. Flow chart for subroutine EFLD1 (Sheet 2 of 3).



2
START LOOP OVER GRID POINTS
\|V – OLDV\| < 1
NO
C
YES
END LOOP OVER GRID POINTS
CALCULATE CDNSTY (NX, 1)
START LOOP ALONG LINE DC
CALCULATE CDNSTY ALONG LINE DC
END LOOP ALONG LINE DC
CALCULATE AVERAGE CURRENT DENSITY AT PLATE (ACDNTY)
ACDNTY > MAXJ
YES
ADJUST QZERO DOWNWARD
A
NO
ACDNTY < MINJ
YES
ADJUST QZERO UPWARD
A
NO
CALCULATE AVERAGE ELECTRIC FIELD AT PLATE (AEPLT)
B
CVERGE = QZERO
VO = – VO
END SUBROUTINE

Figure 14. Flow chart for subroutine EFLD1 (Sheet 3 of 3).

VERGE - Initial estimate of space charge density at the wire ($coul/m^3$).

CVERGE - Final value of space charge density at the wire for convergence ($coul/m^3$).

The following is a list of the necessary variables which are in common with the main program.

VCOOP(I,J) - Initial estimate of potential at points in the grid (V). I and J can not exceed a value of 15.

NPRNT - Indicator which specifies the logical unit number of the printer.

Of the above variables, the values of the following must be provided by the main program: UEQ, CD, AC, VO, SX, SY, NX, NY, TDK, P, VCOOP, and NPRNT. AEPLT, VERGE, and CVERGE are determined in the subroutine. The restrictions on I and J limit the number of grid points in the x-direction and the number of grid points in the y-direction, respectively. If convergence on the electric potential grid can not be obtained in 2000 iterations, a message stating that convergence can not be obtained is printed and the subroutine returns to the main program with those values which were calculated in the last iteration. If convergence on the average current density at the plate can not be obtained in 25 iterations, a message stating that convergence can not be obtained is printed and the subroutine returns to the main program with those values which were calculated in the last iteration.

Subroutine EFLD2

This subroutine calculates a voltage-current curve up to a specified value of operating applied voltage and calculates the average electric field at the plate for the operating applied voltage. The voltage-current curve is generated by (1) specifying a starting value of average current density at the plate, (2) incrementing upward on the average current density, and (3) determining the applied voltage at each value of current density. Once a value of current density results in an applied voltage which exceeds the specified operating applied voltage, an interpolation is performed in order to obtain the operating applied voltage and current density. At the operating applied voltage, calculations can also be made to give the average current density, average electric field, and average electric field at the plate in subincremental lengths.

The equations which are solved and the mathematical technique which is used to solve these equations are the same as discussed for subroutine EFLD1. The major differences in the two subroutines are the use of different boundary conditions in solving equations

(29) and (34) and an added loop in EFLD2 which runs over values of average current density at the plate.

The boundary conditions imposed on the solutions to equations (29) and (34) are:

(1) J_p = given average current density at the plate;

(2) $\rho = \rho_s$, space charge density near the wire and hence,

$\rho = \rho_s = \rho_w$ at point A for calculations outside of r_s;

(3) $E_s r_s = E_c r_w$ = constant;

(4) $E_x = -\frac{\Delta V}{\Delta x} = 0$ and $E_y = -\frac{\Delta V}{\Delta y} = 0$ at points A and B;

(5) V = 0 on the plate or along line CD;

(6) $E_x = -\frac{\Delta V}{\Delta x} = 0$ along line AB;

(7) $E_y = -\frac{\Delta V}{\Delta y} = 0$ along lines BC, CD, and AD;

where r_s = radius of the ionized sheath (m),

E_s = electric field at the outer radius of the ionized sheath (V/m),

E_c = corona starting electric field (V/m), and

r_w = radius of the corona wire (m).

By using the above boundary conditions, solutions to equations (29) and (34) can be obtained without measured or known data.

The steps in the numerical procedure are outlined as follows:

1. Choose an average current density at the plate which corresponds to the lowest value desired on a current-voltage curve.

2. Estimate the potential at the wire that would produce the chosen value of average current density at the plate and calculate V at every point in the grid using equation (26).

3. Calculate ρ at every point in the grid using equation (34), where the space charge density at the wire is given by equation (39).

4. Recalculate V at every point in the grid using equation (29).

5. Repeat steps (3) and (4) alternately until each value of V in the potential grid changes negligibly from its previous value.

6. Check to see if the computed average current density at the plate equals the chosen value. If they agree, then the solution has been obtained. If they do not agree, adjust the potential at the wire and start the calculation over at step (3) above.

7. Choose a larger value of average current density at the plate and obtain a new solution by starting at step (3) with the existing potential grid used to estimate the actual potential grid.

8. Repeat steps (3)-(7) until the desired current-voltage curve is obtained.

In the above procedure, the electric potential at the wire is adjusted until solutions are found which satisfy equations (29) and (34) and the boundary conditions, whereas, in EFLD1, the space charge density at the wire is adjusted.

Figure 15 shows a detailed flow chart for this subroutine. Information which is transmitted between the main program and this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

UEQ - Effective charge carrier mobility (m^2/V-sec).

AC - Radius of discharge electrode (m).

VO - Chosen operating applied voltage (V).

SX - Wire-to-plate spacing (m).

SY - One-half wire-to-wire spacing (m).

NX - Number of grid points in the x-direction. Can not exceed a value of 15.

NY - Number of grid points in the y-direction. Can not exceed a value of 15.

AEPLT - Average electric field at the plate (V/m).

TDK - Temperature of the gas (°K).

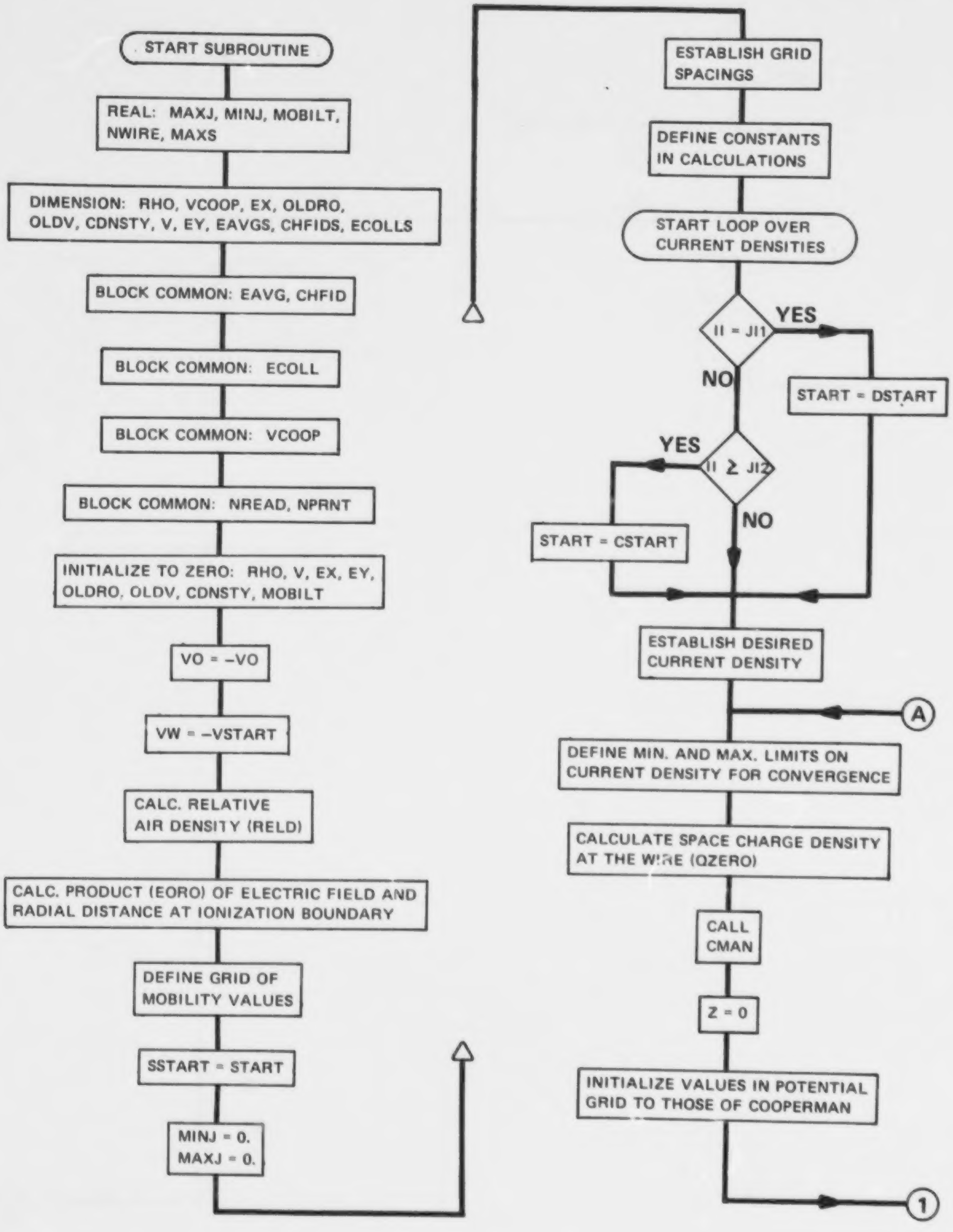

START SUBROUTINE
REAL: MAXJ, MINJ, MOBILT, NWIRE, MAXS
DIMENSION: RHO, VCOOP, EX, OLDRO, OLDV, CDNSTY, V, EY, EAVGS, CHFIDS, ECOLLS
BLOCK COMMON: EAVG, CHFID
BLOCK COMMON: ECOLL
BLOCK COMMON: VCOOP
BLOCK COMMON: NREAD, NPRNT
INITIALIZE TO ZERO: RHO, V, EX, EY, OLDRO, OLDV, CDNSTY, MOBILT
VO = −VO
VW = −VSTART
CALC. RELATIVE AIR DENSITY (RELD)
CALC. PRODUCT (EORO) OF ELECTRIC FIELD AND RADIAL DISTANCE AT IONIZATION BOUNDARY
DEFINE GRID OF MOBILITY VALUES
SSTART = START
MINJ = 0.
MAXJ = 0.
ESTABLISH GRID SPACINGS
DEFINE CONSTANTS IN CALCULATIONS
START LOOP OVER CURRENT DENSITIES
II = JI1
YES
NO
START = DSTART
II ≥ JI2
YES
NO
START = CSTART
ESTABLISH DESIRED CURRENT DENSITY
A
DEFINE MIN. AND MAX. LIMITS ON CURRENT DENSITY FOR CONVERGENCE
CALCULATE SPACE CHARGE DENSITY AT THE WIRE (QZERO)
CALL CMAN
Z = 0
INITIALIZE VALUES IN POTENTIAL GRID TO THOSE OF COOPERMAN
1

Figure 15. Flow chart for subroutine EFLD2 (Sheet 1 of 8).

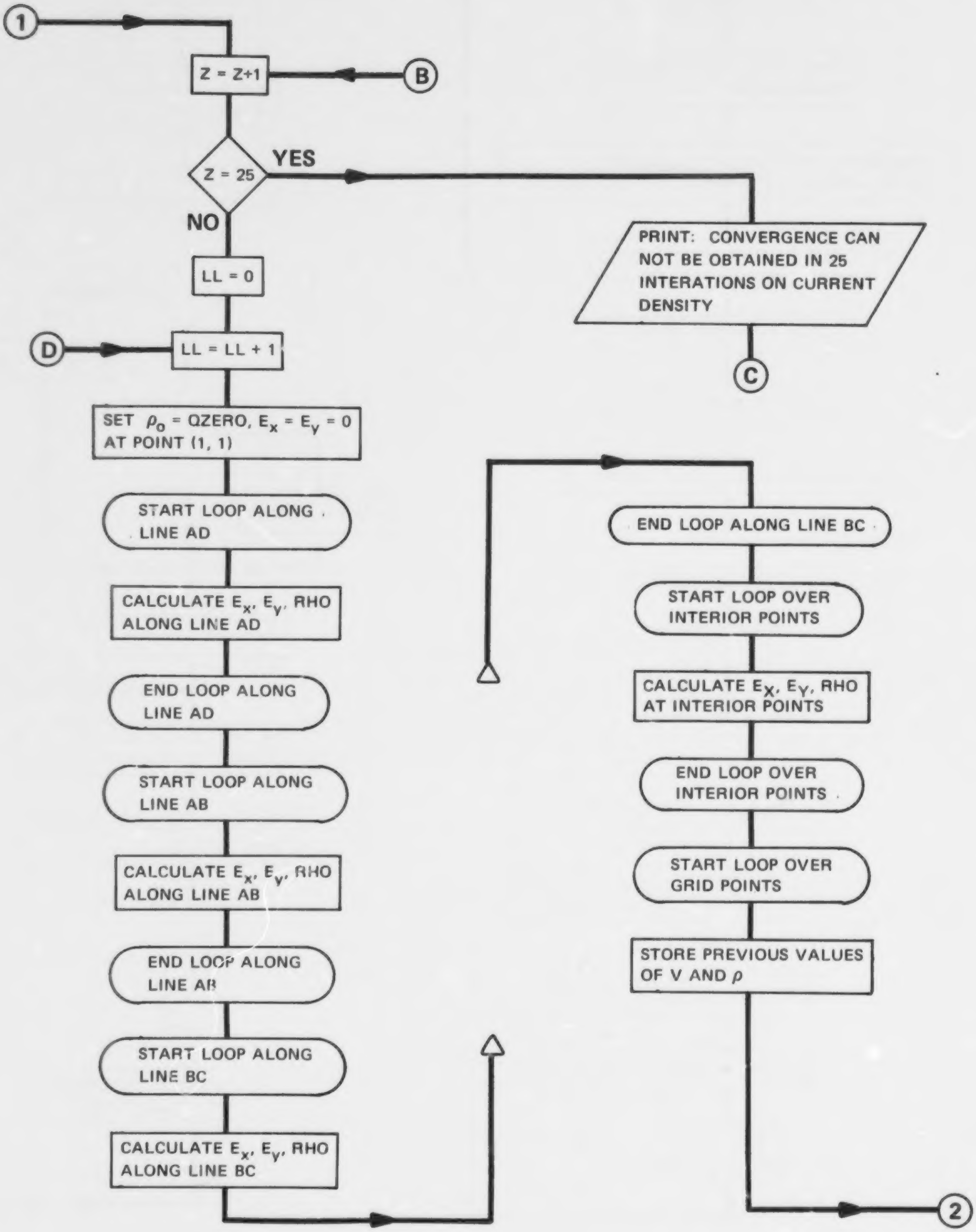
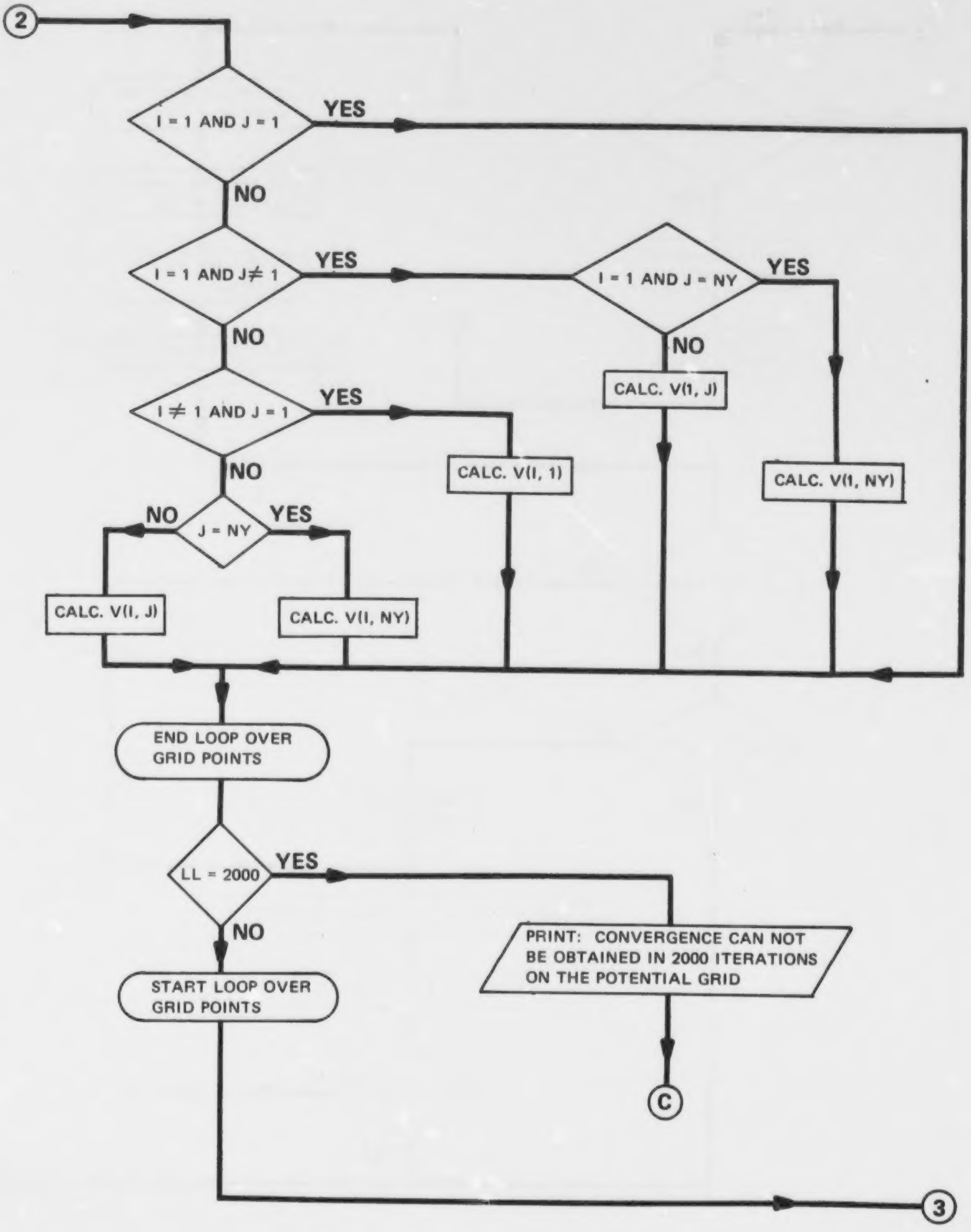

①
Z = Z+1
Ⓑ
Z = 25
YES
NO
PRINT: CONVERGENCE CAN NOT BE OBTAINED IN 25 INTERATIONS ON CURRENT DENSITY
Ⓒ
LL = 0
Ⓓ
LL = LL + 1
SET ρ_o = QZERO, $E_x = E_y = 0$ AT POINT (1, 1)
START LOOP ALONG LINE AD
CALCULATE E_x, E_y, RHO ALONG LINE AD
END LOOP ALONG LINE AD
START LOOP ALONG LINE AB
CALCULATE E_x, E_y, RHO ALONG LINE AB
END LOOP ALONG LINE AB
START LOOP ALONG LINE BC
CALCULATE E_x, E_y, RHO ALONG LINE BC
END LOOP ALONG LINE BC
START LOOP OVER INTERIOR POINTS
CALCULATE E_X, E_Y, RHO AT INTERIOR POINTS
END LOOP OVER INTERIOR POINTS
START LOOP OVER GRID POINTS
STORE PREVIOUS VALUES OF V AND ρ
②

Figure 15. Flow chart for subroutine EFLD2 (Sheet 2 of 8).



2
I = 1 AND J = 1
YES
NO
I = 1 AND J ≠ 1
YES
NO
I = 1 AND J = NY
YES
NO
CALC. V(1, J)
I ≠ 1 AND J = 1
YES
NO
CALC. V(I, 1)
CALC. V(1, NY)
NO
J = NY
YES
CALC. V(I, J)
CALC. V(I, NY)
END LOOP OVER GRID POINTS
LL = 2000
YES
NO
PRINT: CONVERGENCE CAN NOT BE OBTAINED IN 2000 ITERATIONS ON THE POTENTIAL GRID
START LOOP OVER GRID POINTS
C
3

Figure 15. Flow chart for subroutine EFLD2 (Sheet 3 of 8).

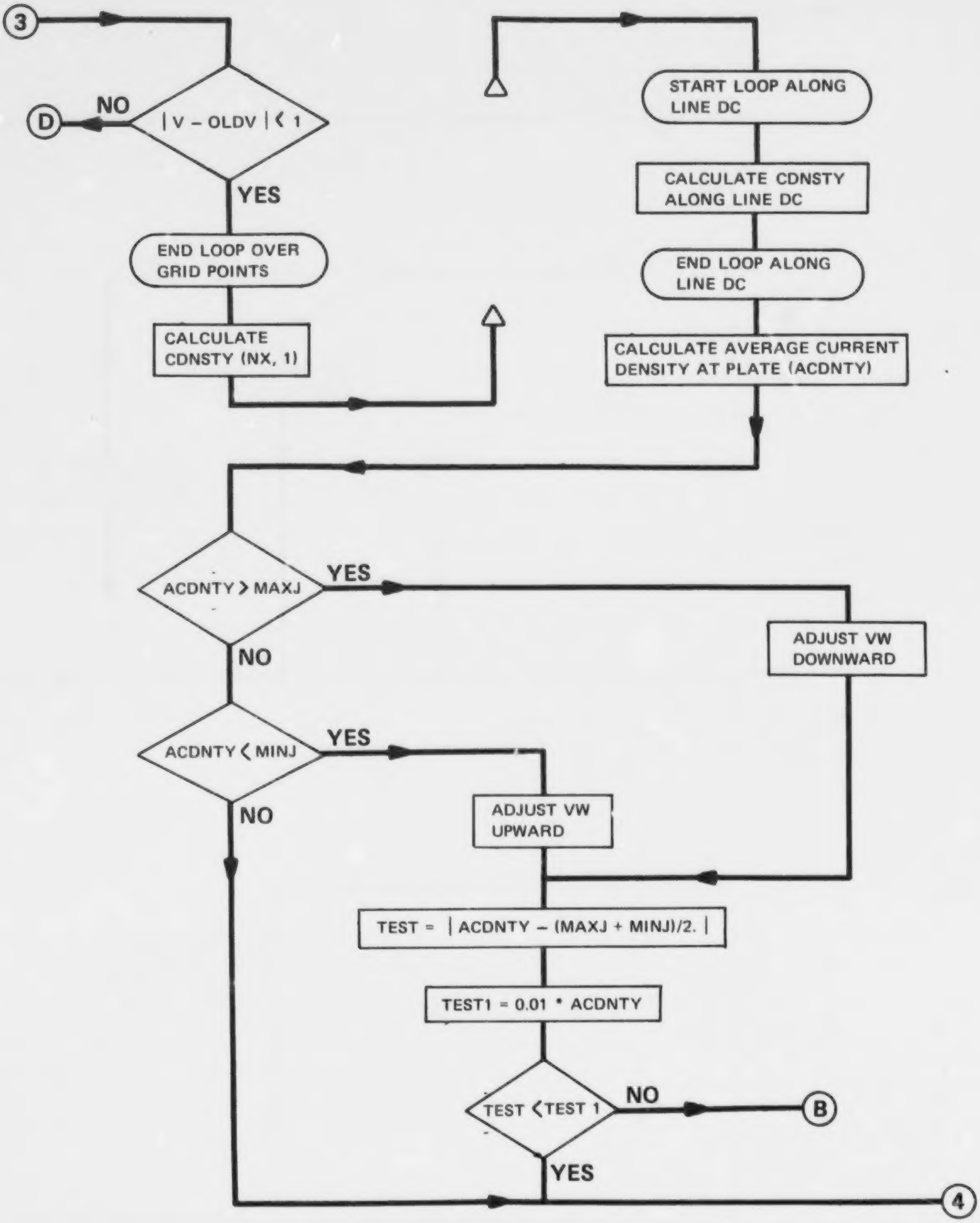

3
|V – OLDV| < 1
NO
D
YES
END LOOP OVER GRID POINTS
CALCULATE CDNSTY (NX, 1)
START LOOP ALONG LINE DC
CALCULATE CDNSTY ALONG LINE DC
END LOOP ALONG LINE DC
CALCULATE AVERAGE CURRENT DENSITY AT PLATE (ACDNTY)
ACDNTY > MAXJ
YES
NO
ADJUST VW DOWNWARD
ACDNTY < MINJ
YES
NO
ADJUST VW UPWARD
TEST = |ACDNTY – (MAXJ + MINJ)/2.|
TEST1 = 0.01 * ACDNTY
TEST < TEST 1
NO
B
YES
4

Figure 15. Flow chart for subroutine EFLD2 (Sheet 4 of 8).

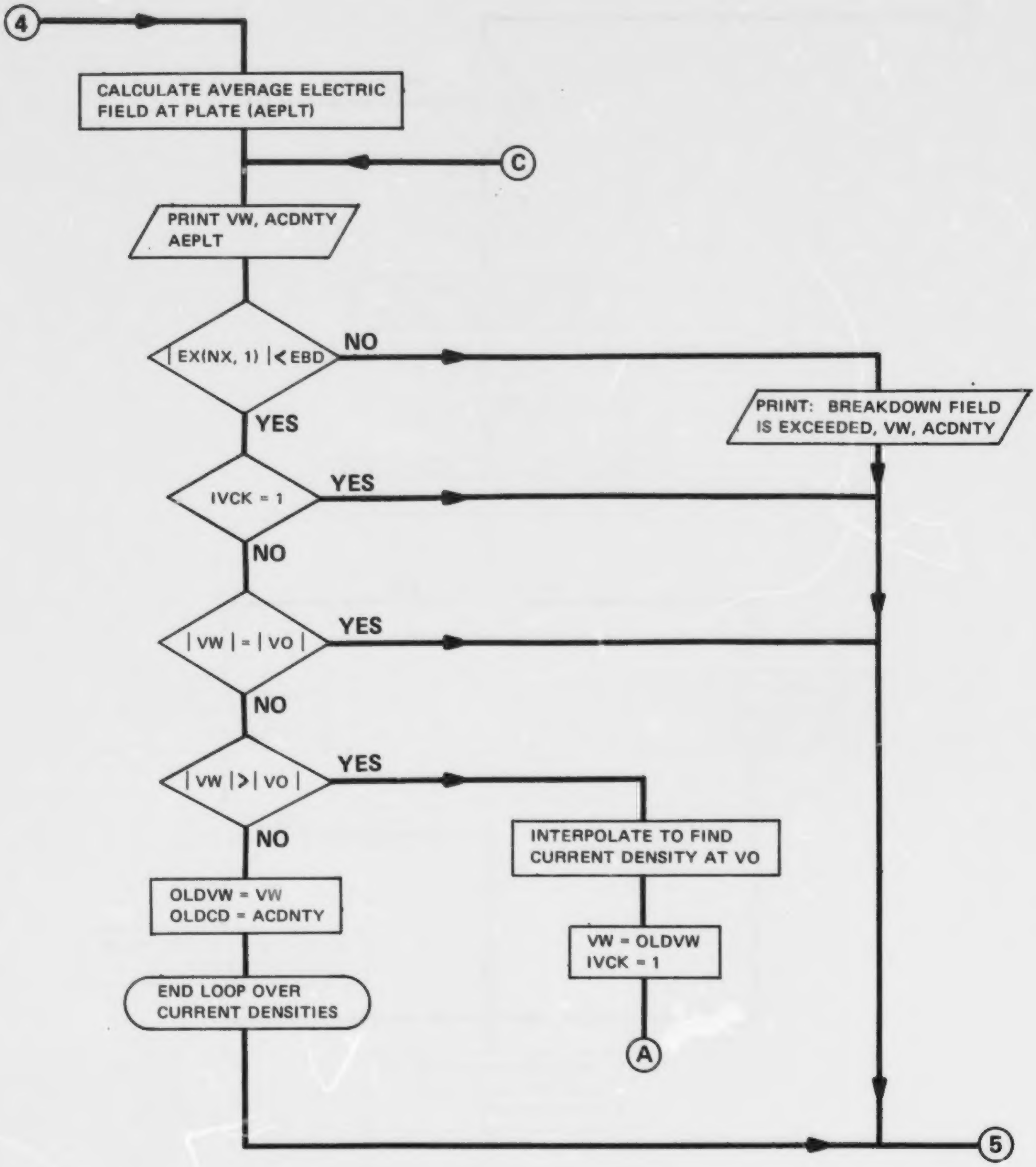

4
CALCULATE AVERAGE ELECTRIC FIELD AT PLATE (AEPLT)
C
PRINT VW, ACDNTY AEPLT
|EX(NX, 1)| < EBD
NO
YES
PRINT: BREAKDOWN FIELD IS EXCEEDED, VW, ACDNTY
IVCK = 1
YES
NO
|VW| = |VO|
YES
NO
|VW| > |VO|
YES
NO
INTERPOLATE TO FIND CURRENT DENSITY AT VO
OLDVW = VW
OLDCD = ACDNTY
VW = OLDVW
IVCK = 1
END LOOP OVER CURRENT DENSITIES
A
5

Figure 15. Flow chart for subroutine EFLD2 (Sheet 5 of 8).

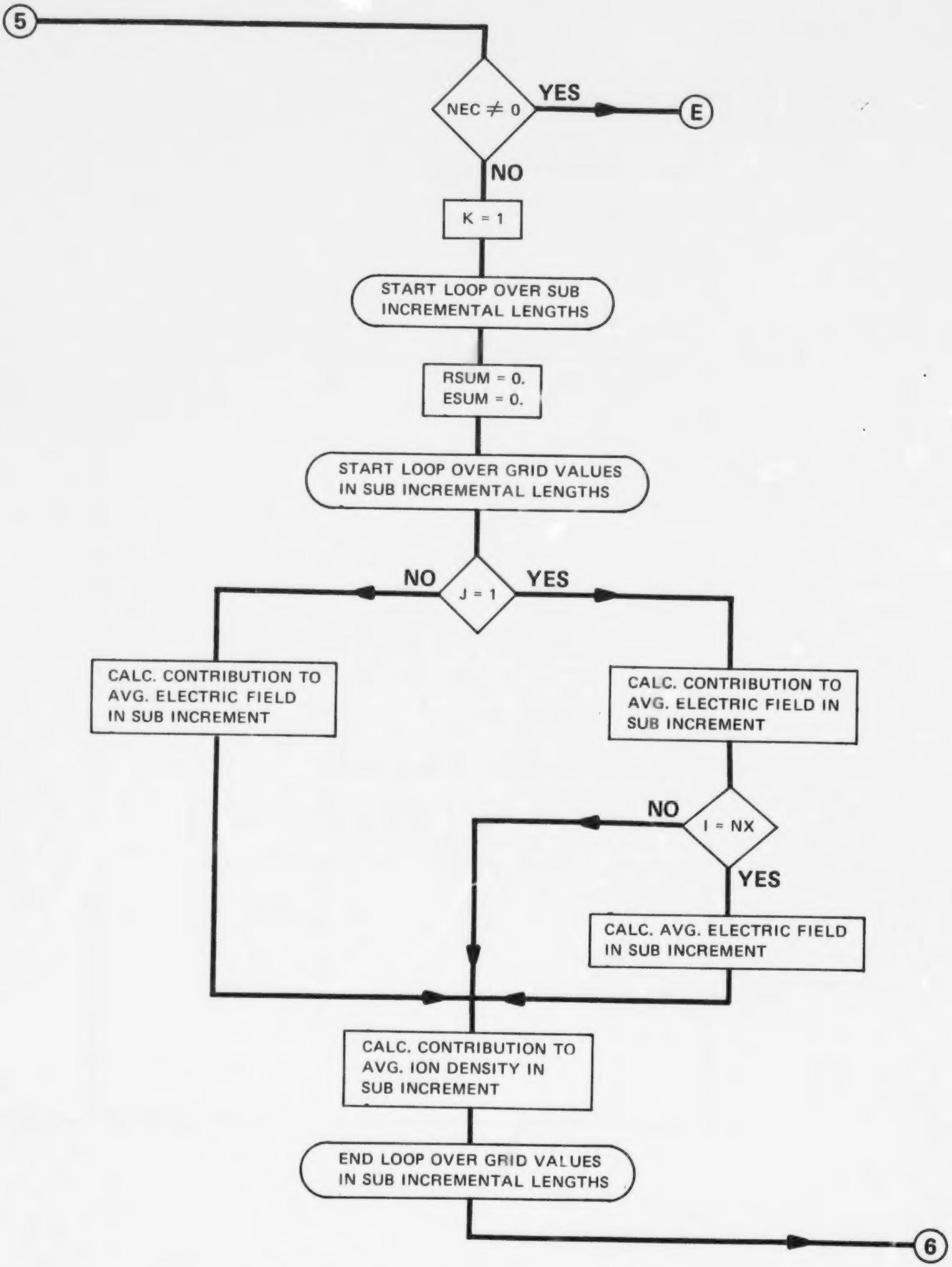

5
NEC ≠ 0
YES
E
NO
K = 1
START LOOP OVER SUB INCREMENTAL LENGTHS
RSUM = 0.
ESUM = 0.
START LOOP OVER GRID VALUES IN SUB INCREMENTAL LENGTHS
NO
J = 1
YES
CALC. CONTRIBUTION TO AVG. ELECTRIC FIELD IN SUB INCREMENT
CALC. CONTRIBUTION TO AVG. ELECTRIC FIELD IN SUB INCREMENT
NO
I = NX
YES
CALC. AVG. ELECTRIC FIELD IN SUB INCREMENT
CALC. CONTRIBUTION TO AVG. ION DENSITY IN SUB INCREMENT
END LOOP OVER GRID VALUES IN SUB INCREMENTAL LENGTHS
6

Figure 15. Flow chart for subroutine EFLD2 (Sheet 6 of 8).

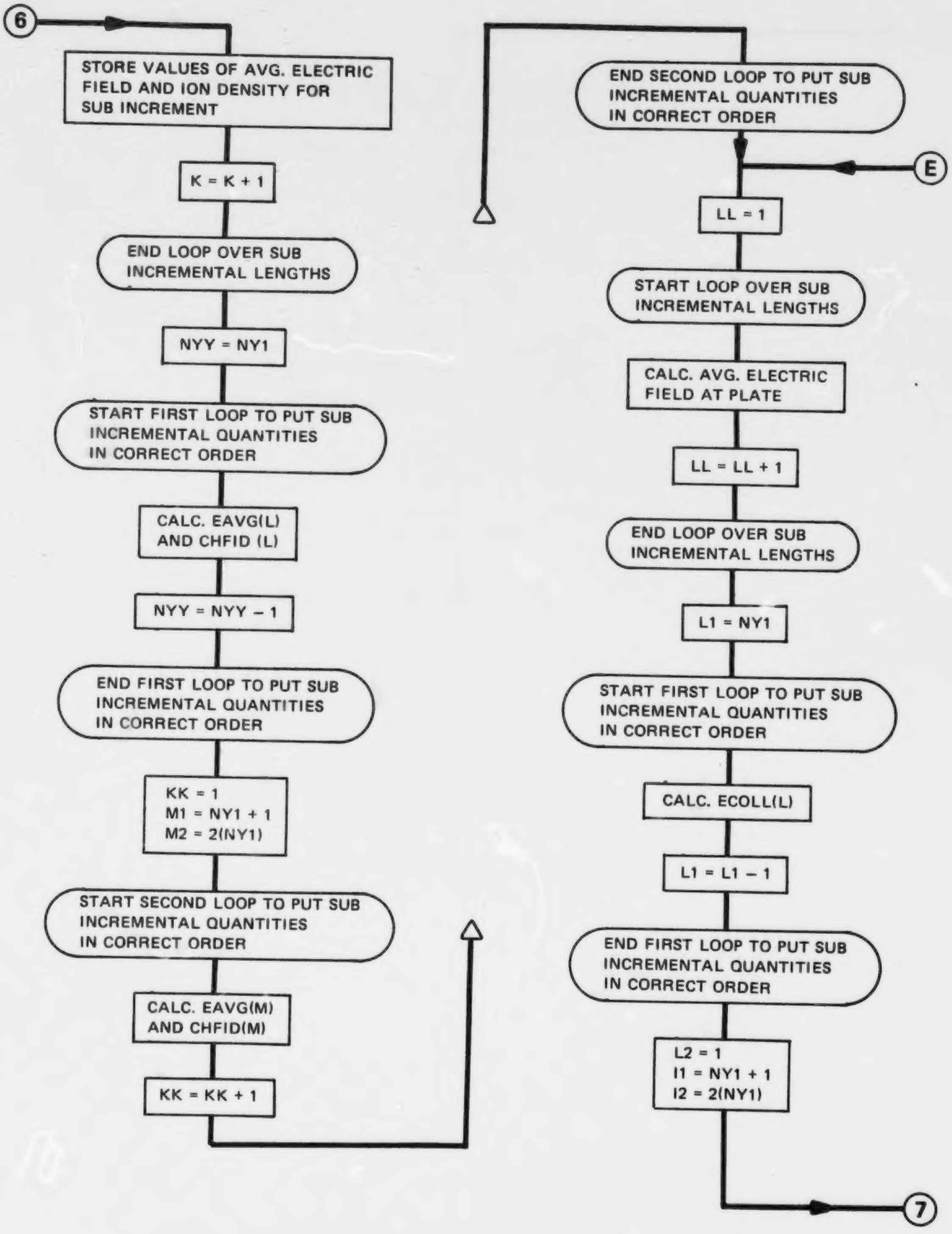

6
STORE VALUES OF AVG. ELECTRIC FIELD AND ION DENSITY FOR SUB INCREMENT
K = K + 1
END LOOP OVER SUB INCREMENTAL LENGTHS
NYY = NY1
START FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. EAVG(L) AND CHFID (L)
NYY = NYY – 1
END FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
KK = 1
M1 = NY1 + 1
M2 = 2(NY1)
START SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. EAVG(M) AND CHFID(M)
KK = KK + 1
END SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
E
LL = 1
START LOOP OVER SUB INCREMENTAL LENGTHS
CALC. AVG. ELECTRIC FIELD AT PLATE
LL = LL + 1
END LOOP OVER SUB INCREMENTAL LENGTHS
L1 = NY1
START FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. ECOLL(L)
L1 = L1 – 1
END FIRST LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
L2 = 1
I1 = NY1 + 1
I2 = 2(NY1)
7

Figure 15. Flow chart for subroutine EFLD2 (Sheet 7 of 8).

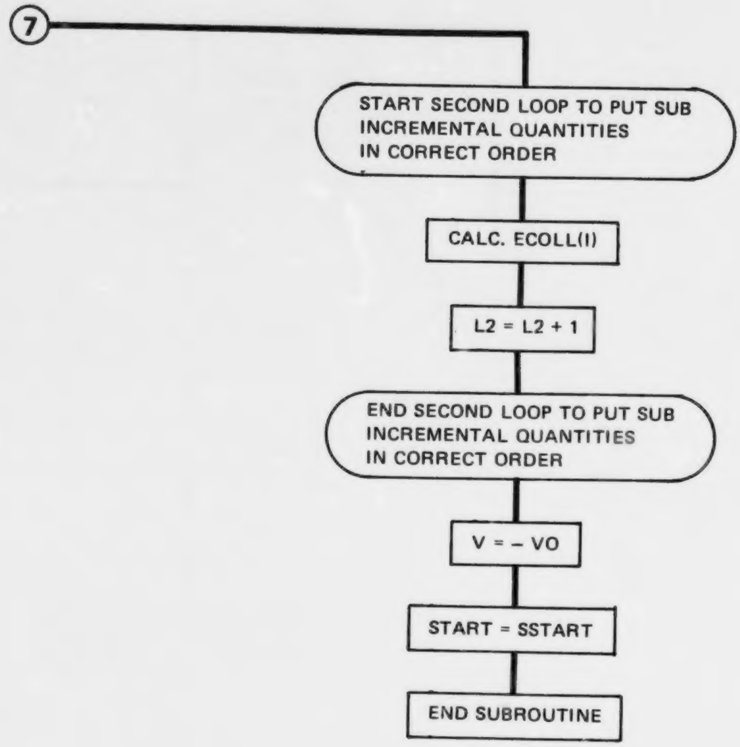

7
START SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
CALC. ECOLL(I)
L2 = L2 + 1
END SECOND LOOP TO PUT SUB INCREMENTAL QUANTITIES IN CORRECT ORDER
V = – VO
START = SSTART
END SUBROUTINE

Figure 15. Flow chart for subroutine EFLD2 (Sheet 8 of 8).

P - Pressure of the gas (atm).

RF - Roughness factor for the discharge wire ($0.5 \leq RF \leq 1.0$).

START - Chosen initial current density at which the voltage-current curve calculation starts (A/m^2). Current densities increment in values of START until a change is specified.

DSTART - Chosen increment in current density which is used in place of START when specified (A/m^2).

CSTART - Chosen increment in current density which is used in place of DSTART when specified (A/m^2).

IFINAL - Indicator which terminates the loop over average current densities at the plate after IFINAL times.

VSTART - Initial estimate of applied voltage corresponding to first value of average current density at the plate on the voltage-current curve (V).

VW - Operating applied voltage corresponding to a given current density (V).

ACDNTY - Average current density at the plate (A/m^2).

NWIRE - Number of wires per gas passage per electrical section.

NEC - Indicator which governs the calculations of average current density, average electric field, and average electric field at the plate in subincremental lengths. The calculations are performed when NEC = 0 and are not performed when NEC = 1.

EBD - Electrical breakdown strength of the gas (V/m).

JI1 - Indicator which governs the change in the increment on average current density at the plate from START TO DSTART. The change occurs on the JI1-th value of current density.

JI2 - Indicator which governs the change in the increment on average current density at the plate from DSTART to CSTART. The change occurs on the JI2-th value of current density.

The following is a list of the variables which are in common with the main program.

EAVG(M) - Average electric field in a given subincrement of length (V/m). M can not exceed the value of 30.

CHFID(M) - Average ion density in the absence of particles in a given subincrement of length (#/m^3). M can not exceed a value of 30.

ECOLL(M) - Average electric field at the plate in a given subincrement of length (V/m). M can not exceed the value of 30.

VCOOP(I,J) - Initial estimate of potential at points in the grid (V). I and J can not exceed a value of 15.

NPRNT - Indicator which specifies the logical unit number of the printer.

Of the above variables, the values of the following must be provided by the main program: UEQ, AC, VO, SX, SY, NX, NY, TDK, P, RF, START, DSTART, CSTART, IFINAL, VSTART, NWIRE, NEC, EBD, JI1, JI2, and NPRNT. AEPLT, VW, ACDNTY, EAVG, CHFID, ECOLL, and VCOOP are determined in the subroutine. The restrictions on I, J, and M limit the number of grid points in the x-direction, the number of grid points in the y-direction, and the number of subincremental lengths in a given length increment, respectively. The subroutine calls subroutine CMAN in order to determine VCOOP.

If, for a given current density, convergence on the electric potential grid can not be obtained in 2000 iterations, a message stating that convergence can not be obtained is printed and those values which were calculated in the last iteration are used for that particular point on the voltage-current curve. If convergence on a given average current density at the plate can not be obtained in 25 iterations, a message stating that convergence can not be obtained is printed and those values which were calculated in the last iteration are used for that particular point on the voltage-current curve.

There are three possible conditions which will result in termination of the voltage-current curve at a particular voltage and current. The curve is terminated if (1) the specified operating applied voltage is reached, or (2) the number of points on the curve is equal to value of IFINAL, or (3) the specified value of electrical breakdown strength near the collection electrode is exceeded. If the breakdown strength is exceeded, a message stating that this is the case is printed.

Subroutine CHARGN

This subroutine calculates particle charge as a function of residence time, electrical conditions, gas conditions, and particle characteristics. In order to use this subroutine, statement function RATE and subroutines ARCCOS and ZERO are required.

The subroutine determines particle charge by solving equation (12). Equation (12) is a first-order differential equation of the form

$$\frac{dy}{dx} = f(x,y) \tag{40}$$

with initial values x_0 and y_0 and is solved numerically using a quartic Runge-Kutta method.[33] This is a single-step method in which the value of y at $x = x_n$ is used to compute $y_{n+1} = y(x_{n+1})$ and earlier values y_{n-1}, y_{n-2}, etc. are not used.

The increment for advancing the dependent variable is given by

$$\Delta y = \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4) \tag{41}$$

where, for a given stepsize h,

$$k_1 = hf(x_n, y_n) \quad , \tag{42}$$

$$k_2 = hf(x_n + \frac{1}{2}h, y_n + \frac{1}{2} k_1) \quad , \tag{43}$$

$$k_3 = hf(x_n + \frac{1}{2}h, y_n + \frac{1}{2} k_2) \quad , \tag{44}$$

and

$$k_4 = hf(x_n + h, y_n + k_3) \quad . \tag{45}$$

The values at (x_{n+1}, y_{n+1}) are given by

$$x_{n+1} = x_n + h \tag{46}$$

and

$$y_{n+1} = y_n + \Delta y \quad . \tag{47}$$

The subroutine calls the statement function RATE to calculate the right hand side of equation (12) at the function values specified in equations (42)-(45).

The numerical procedure for finding solutions to equation (12) consists of the following steps.

1. The initial conditions are taken to be $q = 0$ at $t = 0$.

2. q_s is calculated in the main program using equation (13) and is supplied to subroutine CHARGN and statement function RATE.

3. For each value of q required in the Runge-Kutta scheme, a value of θ_0 is calculated in statement function RATE using equation (14).

4. The integration over θ on the right hand side of equation (12) is performed in statement function RATE using Simpson's Rule. For each value of θ which is chosen for this integration, the radial distance (r_0) from the center of the particle and along θ for which the total electric field is zero is calculated using subroutine ZERO.

5. The three individual charging rates are calculated and then added in statement function RATE to give the total instantaneous charging rate for a particular value of q.

6. The total charging rates necessary for use in equations (41)-(45) are obtained by subroutine CHARGN and q and t are obtained from equations (46) and (47).

Figure 16 shows a detailed flow chart for this subroutine. All information which is transmitted between the main program and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

ECHARG - Value of an electronic charge unit (coul).

SCHARG - Value of saturation charge number from the field charging equation [see eq. (13)].

NUMINC - Number of increments in the Simpson's Rule integration over θ. A value of 20 is normally sufficient.

CONST - Value of the quantity $[2 \frac{(K-1)}{(K+2)} a^3 E_0]$ found in equation (12) [V-m^2].

EZERO - Applied electric field strength for particle charging (V/m).

V - Value of the quantity $[\frac{e^2}{4\pi\varepsilon_0 akT}]$ found in equation (12).

RSIZE - Radius of the particle (m).

ECONST - Value of the quantity $[\frac{3eE_0 a}{kT(K+2)}]$ found in equation (12).

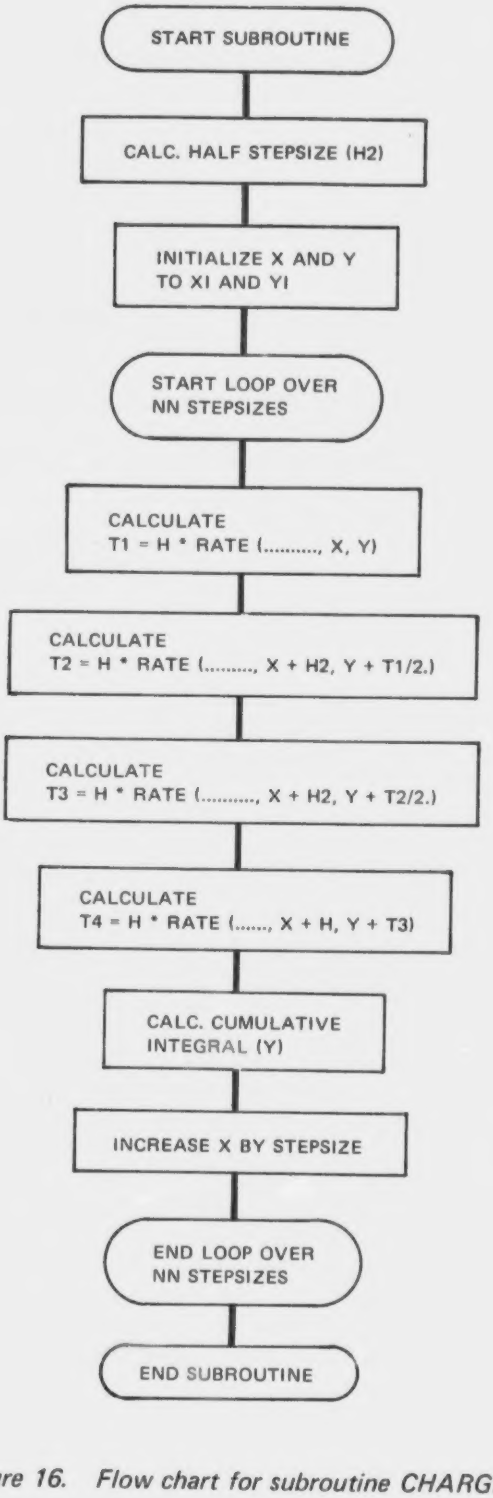

START SUBROUTINE
CALC. HALF STEPSIZE (H2)
INITIALIZE X AND Y TO XI AND YI
START LOOP OVER NN STEPSIZES
CALCULATE T1 = H * RATE (.........., X, Y)
CALCULATE T2 = H * RATE (........., X + H2, Y + T1/2.)
CALCULATE T3 = H * RATE (.........., X + H2, Y + T2/2.)
CALCULATE T4 = H * RATE (......, X + H, Y + T3)
CALC. CUMULATIVE INTEGRAL (Y)
INCREASE X BY STEPSIZE
END LOOP OVER NN STEPSIZES
END SUBROUTINE

Figure 16. Flow chart for subroutine CHARGN.

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $(\text{coul}^2/\text{nt-m}^2)$.

RR - Value of the quantity $[\frac{eE_0}{kT}]$ found in equation (12) $[\text{m}^{-1}]$.

FCONST - Value of the quantity $[\frac{(k-1)eE_0a^3}{(k+2)kT}]$ found in equation (12) $[\text{m}^2]$.

FACTOR - Value of the quantity $[\frac{\pi\tilde{v}a^2}{2}]$ found in equation (12) $[\text{m}^3/\text{sec}]$.

COEFF - Value of the quantity $[\frac{bq_s}{4E_0}]$ found in equation (12) $[\text{m}^3/\text{sec}]$.

AFID - Free ion density for particle charging $(\#/\text{m}^3)$.

RATE - Statement function which must be supplied to subroutine CHARGN.

H - Increment size for Runge-Kutta integration (sec).

XI - Initial value of time (sec).

YI - Initial value of charge number.

NN - Number of increments in the Runge-Kutta integration. A value of 10 is normally sufficient.

X - Final value of time (sec).

Y - Final value of charge number.

Of the above variables, the values of the following must be provided by the main program: ECHARG, SCHARG, NUMINC, CONST, EZERO, V, RSIZE, ECONST, RR, FCONST, FACTOR, COEFF, AFID, RATE, H, XI, YI, and NN. X and Y are determined in the subroutine.

For length increments along the precipitator of approximately 0.305 meter or less, the use of 10 increments in the Runge-Kutta integration and 20 increments in the Simpson's Rule integration yields solutions to equation (12) which are changed negligibly by increasing the number of points used. In cases where the use of computer time is a significant consideration, the use of 5 increments in the Runge-Kutta integration and 10 increments in the Simpson's Rule integration will result in charge values which are not severely changed. These values of NN and NUMINC should be regarded as yielding a lower limit for which reliability can be expected and they should not be reduced further.

Statement Function RATE

This statement function calculates the right hand side of equation (12) for use in subroutine CHARGN. In order to use this statement function, subroutines ARCCOS and ZERO must be supplied.

The first and third terms on the right hand side of equation (12) are calculated in a straightforward manner. However, the third term involves an integration over the angle θ which must be performed numerically. The integration is performed by using Simpson's Rule[34] which is given by

$$\int_{x_0}^{x_n} y(x)\,dx \simeq \frac{h}{3}\,(y_0 + 4y_1 + 2y_2 + 4y_3 + 2y_4 + \cdots\cdots + 4y_{n-1} + y_n) \;, \tag{48}$$

where

$$x_i = x_0 + ih \quad (i = 0,1,2, \cdots\cdots n) \;, \tag{49}$$

n is even, and h is the increment size. In the application of this technique, there must be an odd number of points.

The subroutine performs the operations indicated in equation (48) by first calculating the odd-numbered function values and summing them. Next, the even-numbered function values are calculated and those between y_0 and y_n are summed. Thus, equation (48) is applied in the form

$$\int_{x_0}^{x_n} y(x)\,dx \simeq \frac{h}{3}\,(y \;+ 4\sum_{n\ \mathrm{even}} y_n \;+ 2\sum_{n\ \mathrm{odd}} y_n + y_n) \quad . \tag{50}$$

The lower integration limit θ_0 in the second term of equation (12) is determined by calling subroutine ARCCOS. If θ_0 is less than or equal to 0.00001 radian, it is set equal to zero. For each value of θ in the integration, the radial distance (r_0) from the center of the particle and along θ for which the total electric field is zero is determined by calling subroutine ZERO.

If the charge on the particle is equal to or greater than the saturation charge, the first term on the right hand side of equation (12) is set equal to zero. Once the three terms on the right hand side of equation (12) are calculated, then they are added to give the total charging rate.

Figure 17 shows a detailed flow chart for this subroutine. All information which is transmitted between subroutine CHARGN

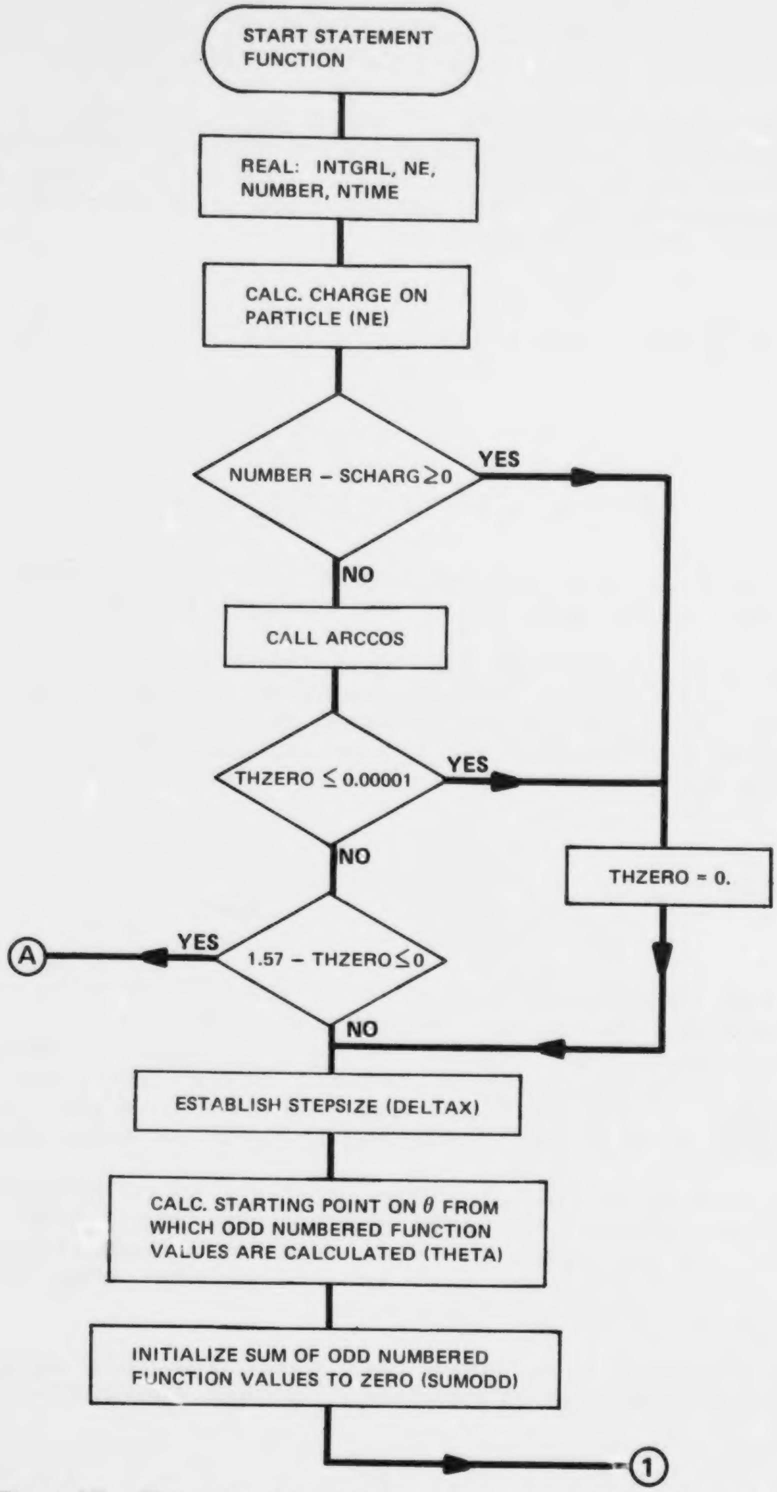

START STATEMENT FUNCTION
REAL: INTGRL, NE, NUMBER, NTIME
CALC. CHARGE ON PARTICLE (NE)
NUMBER – SCHARG ≥ 0
YES
NO
CALL ARCCOS
THZERO ≤ 0.00001
YES
NO
THZERO = 0.
1.57 – THZERO ≤ 0
YES
A
NO
ESTABLISH STEPSIZE (DELTAX)
CALC. STARTING POINT ON θ FROM WHICH ODD NUMBERED FUNCTION VALUES ARE CALCULATED (THETA)
INITIALIZE SUM OF ODD NUMBERED FUNCTION VALUES TO ZERO (SUMODD)
①

Figure 17. Flow chart for statement function RATE (Sheet 1 of 5).

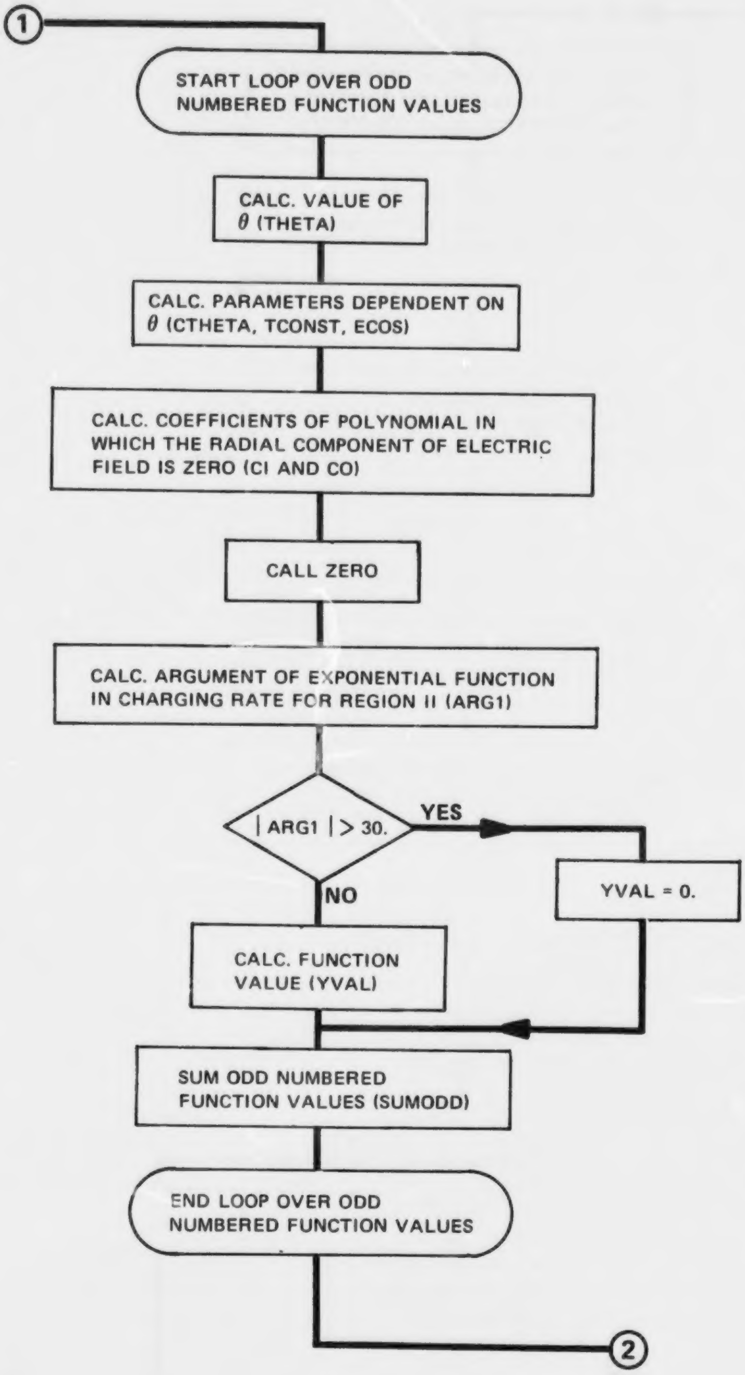

①
START LOOP OVER ODD NUMBERED FUNCTION VALUES
CALC. VALUE OF θ (THETA)
CALC. PARAMETERS DEPENDENT ON θ (CTHETA, TCONST, ECOS)
CALC. COEFFICIENTS OF POLYNOMIAL IN WHICH THE RADIAL COMPONENT OF ELECTRIC FIELD IS ZERO (CI AND CO)
CALL ZERO
CALC. ARGUMENT OF EXPONENTIAL FUNCTION IN CHARGING RATE FOR REGION II (ARG1)
\| ARG1 \| > 30.
YES
NO
YVAL = 0.
CALC. FUNCTION VALUE (YVAL)
SUM ODD NUMBERED FUNCTION VALUES (SUMODD)
END LOOP OVER ODD NUMBERED FUNCTION VALUES
②

Figure 17. Flow chart for statement function RATE (Sheet 2 of 5).

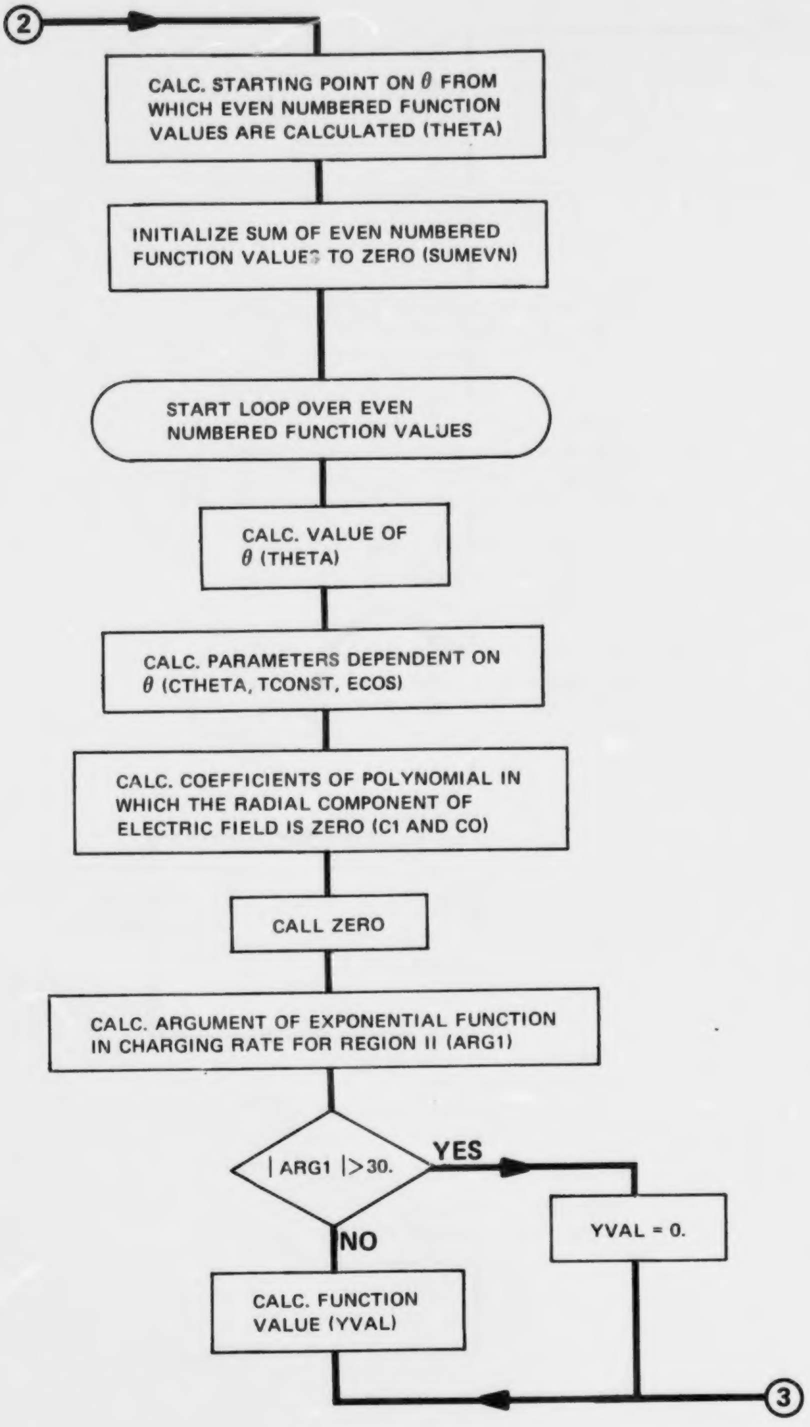

②
CALC. STARTING POINT ON θ FROM WHICH EVEN NUMBERED FUNCTION VALUES ARE CALCULATED (THETA)
INITIALIZE SUM OF EVEN NUMBERED FUNCTION VALUES TO ZERO (SUMEVN)
START LOOP OVER EVEN NUMBERED FUNCTION VALUES
CALC. VALUE OF θ (THETA)
CALC. PARAMETERS DEPENDENT ON θ (CTHETA, TCONST, ECOS)
CALC. COEFFICIENTS OF POLYNOMIAL IN WHICH THE RADIAL COMPONENT OF ELECTRIC FIELD IS ZERO (C1 AND CO)
CALL ZERO
CALC. ARGUMENT OF EXPONENTIAL FUNCTION IN CHARGING RATE FOR REGION II (ARG1)
| ARG1 |>30.
YES
YVAL = 0.
NO
CALC. FUNCTION VALUE (YVAL)
③

Figure 17. Flow chart for statement function RATE (Sheet 3 of 5).

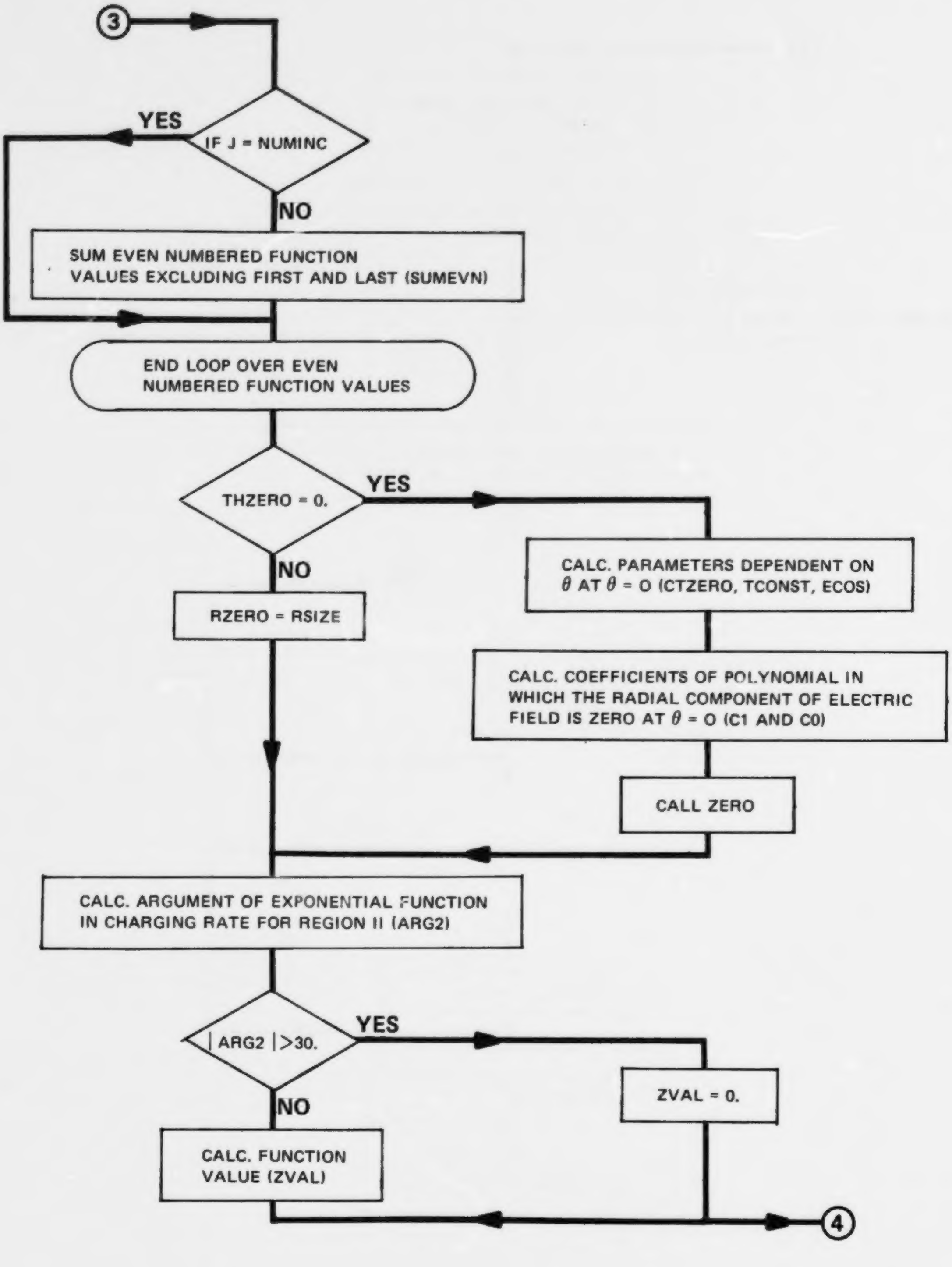

3
IF J = NUMINC
YES
NO
SUM EVEN NUMBERED FUNCTION VALUES EXCLUDING FIRST AND LAST (SUMEVN)
END LOOP OVER EVEN NUMBERED FUNCTION VALUES
THZERO = 0.
YES
NO
CALC. PARAMETERS DEPENDENT ON θ AT θ = O (CTZERO, TCONST, ECOS)
CALC. COEFFICIENTS OF POLYNOMIAL IN WHICH THE RADIAL COMPONENT OF ELECTRIC FIELD IS ZERO AT θ = O (C1 AND C0)
CALL ZERO
RZERO = RSIZE
CALC. ARGUMENT OF EXPONENTIAL FUNCTION IN CHARGING RATE FOR REGION II (ARG2)
| ARG2 | >30.
YES
NO
ZVAL = 0.
CALC. FUNCTION VALUE (ZVAL)
4

Figure 17. Flow chart for statement function RATE (Sheet 4 of 5).

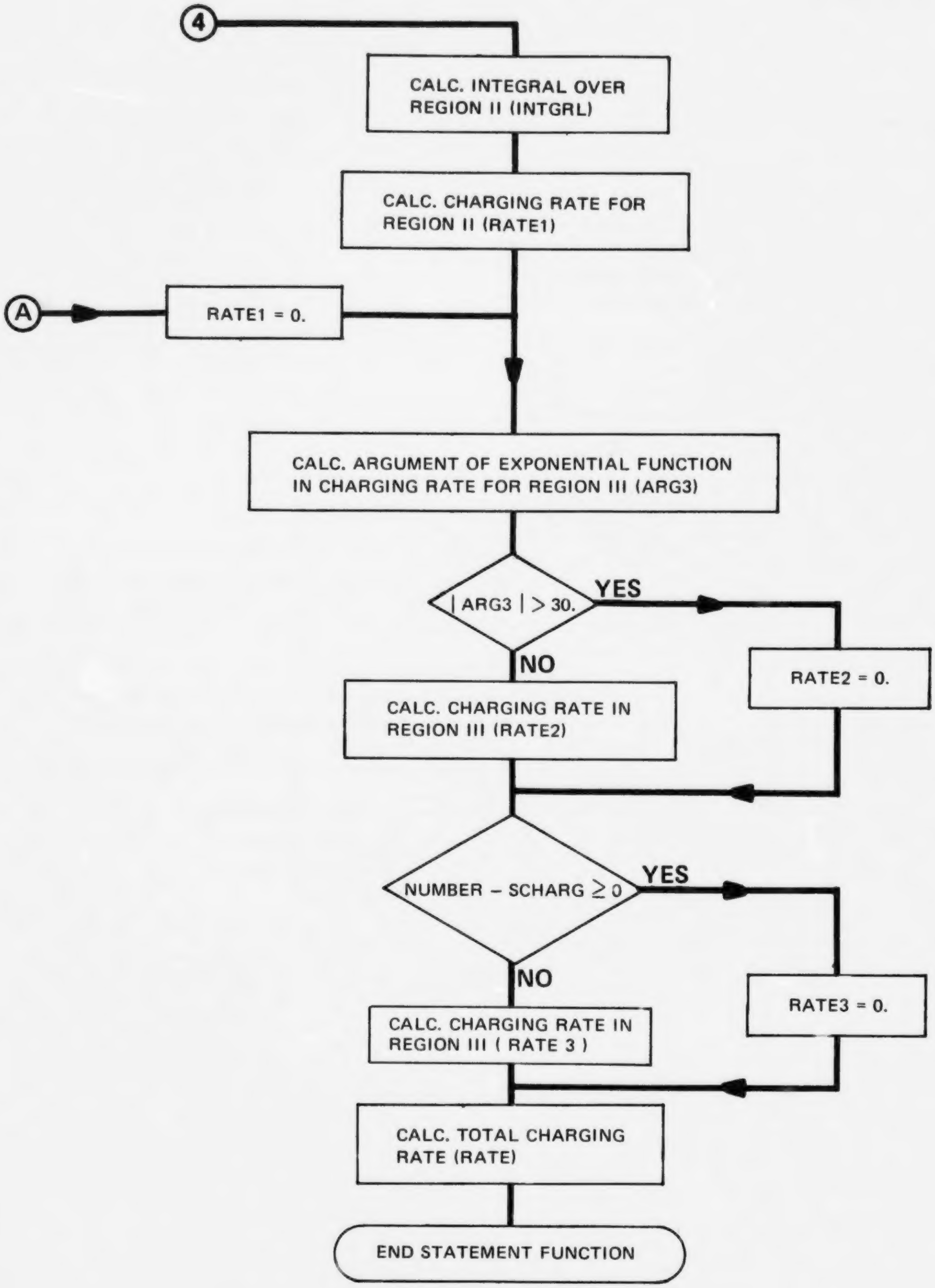

4
CALC. INTEGRAL OVER REGION II (INTGRL)
CALC. CHARGING RATE FOR REGION II (RATE1)
A
RATE1 = 0.
CALC. ARGUMENT OF EXPONENTIAL FUNCTION IN CHARGING RATE FOR REGION III (ARG3)
\| ARG3 \| > 30.
YES
NO
RATE2 = 0.
CALC. CHARGING RATE IN REGION III (RATE2)
NUMBER – SCHARG ≥ 0
YES
NO
RATE3 = 0.
CALC. CHARGING RATE IN REGION III (RATE 3)
CALC. TOTAL CHARGING RATE (RATE)
END STATEMENT FUNCTION

Figure 17. Flow chart for statement function RATE (Sheet 5 of 5).

and this statement function is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

ECHARG - Value of an electronic charge unit (coul).

SCHARG - Value of saturation charge number from the field charging equation [see eq. (13)].

NUMINC - Number of increments in the Simpson's Rule integration over θ. NUMINC must be even and 20 is normally sufficient.

CONST - Value of the quantity $[2 \frac{(K-1)}{(K+2)} a^3 E_0]$ found in equation (12) $[V\text{-}m^2]$.

EZERO - Applied electric field strength for particle charging (V/m).

V - Value of the quantity $[\frac{e^2}{4\pi\varepsilon_0 akT}]$ found in equation (12).

RSIZE - Radius of the particle (m).

ECONST - Value of the quantity $[\frac{3eE_0 a}{kT(K+2)}]$ found in equation (12).

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $(coul^2/nt\text{-}m^2)$.

RR - Value of the quantity $[\frac{eE_0}{kT}]$ found in equation (12) $[m^{-1}]$.

FCONST - Value of the quantity $[\frac{(K-1)eE_0 a^3}{(K+2)kT}]$ found in equation (12) $[m^2]$.

FACTOR - Value of the quantity $[\frac{\pi \tilde{v} a^2}{2}]$ found in equation (12) $[m^3/sec]$.

COEFF - Value of the quantity $[\frac{bq_s}{4E_0}]$ found in equation (12) $[m^3/sec]$.

AFID - Free ion density for particle charging $(\#/m^3)$.

NTIME - Residence time for particle charging (sec).

NUMBER - Particle charge number (coul).

Of the above variables, the values of the following must be provided by subroutine CHARGN: ECHARG, SCHARG, NUMINC, CONST, EZERO, V, RSIZE, ECONST, RR, FCONST, FACTOR, COEFF, AFID, NTIME, and NUMBER. The total charging rate given on the right hand side of equation (12) is RATE and is determined in the statement function.

Subroutine ARCCOS

This subroutine calculates the inverse cosine of a number. The calculation is performed by using the series expansion given by[35]

$$\cos^{-1}x = \frac{\pi}{2} - \left(x + \frac{x^3}{2.3} + \frac{1.3}{2.4.5}\,x^5 + \frac{1.3.5}{2.4.6.7}\,x^7 + \cdots\right) \quad , \qquad (51)$$

where $x^2<1$ and $0<\cos^{-1}x<\pi$.

The subroutine is specialized in that the number x is determined by the ratio A/B of two numbers. This is done because in the particle charging theory the inverse cosine of the ratio of the particle charge to the saturation charge must be calculated. However, the subroutine can be used in general by setting B=1, so that A becomes the number whose inverse cosine is determined. The series in equation (51) is terminated when a term is reached which is equal to or less than 0.00001.

Figure 18 shows a detailed flow chart for this subroutine. All information which is transmitted between this subroutine and other main or subprograms is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

A - Numerator of the ratio A/B whose inverse cosine is to be determined.

B - Denominator of the ratio A/B whose inverse cosine is to be determined.

ACOS - Value of the $\cos^{-1}$ (A/B) [radians].

The variables A and B must be supplied to the subroutine and ACOS is determined in the subroutine.

Subroutine ZERO

This subroutine determines the radial distance (r_0) from the center of a charged particle and along a given angle θ for which the total electric field is zero. The use of this subroutine requires that subroutine ARCCOS be supplied.

From the particle charging theory,[36] the condition that the total electric field be zero is given by

$$r_0{}^3 - \left(\frac{ne}{4\pi\varepsilon_0 E_0 \cos\theta}\right) r_0 + 2\left(\frac{K-1}{K+2}\right) a^3 = 0 \quad , \qquad (52)$$

where the symbols are defined the same as for equation (12).

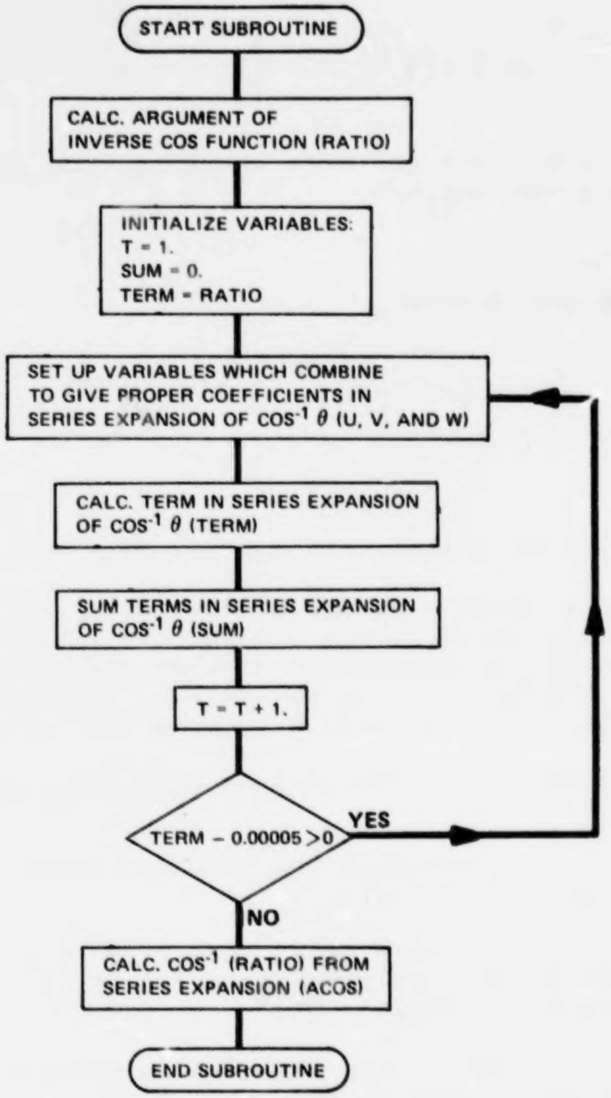

START SUBROUTINE
CALC. ARGUMENT OF INVERSE COS FUNCTION (RATIO)
INITIALIZE VARIABLES:
T = 1.
SUM = 0.
TERM = RATIO
SET UP VARIABLES WHICH COMBINE TO GIVE PROPER COEFFICIENTS IN SERIES EXPANSION OF COS-1 θ (U, V, AND W)
CALC. TERM IN SERIES EXPANSION OF COS-1 θ (TERM)
SUM TERMS IN SERIES EXPANSION OF COS-1 θ (SUM)
T = T + 1.
TERM – 0.00005 >0
YES
NO
CALC. COS-1 (RATIO) FROM SERIES EXPANSION (ACOS)
END SUBROUTINE

Figure 18. Flow chart for subroutine ARCCOS.

For a given angle θ, this is a cubic equation in r_0 of the form

$$x^3 - c_1 x + 2c_2 = 0 \quad . \tag{53}$$

This type of cubic equation has roots given by

$$x = -2\sqrt{\frac{c_1}{3}} \cos \left\{ \frac{\cos^{-1}\sqrt{\frac{27c_2^2}{c_1^3}}}{3} + \frac{2\pi}{3} n \right\} \tag{54}$$

where n = 0,1,2. For particle charging, the physically meaningful solution is given for n=1

$$r_0 = -2\sqrt{\frac{ne}{12\pi\varepsilon_0 E_0 \cos\theta}} \cdot$$

$$\cos\left\{ \frac{\cos^{-1}\sqrt{27\left(\frac{K-1}{K+2}\right)^2 \left(\frac{4\pi\varepsilon_0 a^2 E_0 \cos\theta}{ne}\right)^3}}{3} + \frac{2\pi}{3} \right\} \quad . \tag{55}$$

The subroutine determines r_0 from equation (55).

Figure 19 shows a detailed flow chart for this subroutine. This subroutine is called by statement function RATE and all information which is transmitted between these subprograms is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

C1 - Value of the coefficient $[\frac{q}{4\pi\varepsilon_0 E_0 \cos\theta}]$ of r_0 in equation (52) [m].

C0 - Value of one-half the constant term $[(\frac{K-1}{K+2})\ a^3]$ in equation (52) $[m^4/V]$.

RZERO - Radial distance from the center of a charged particle and along a given angle θ for which the total electric field is zero.

The variables C1 and C0 are supplied by statement function RATE and RZERO is determined in the subroutine.

Subroutine CHGSUM

This subroutine calculates particle charge as a function of residence time, electrical conditions, gas conditions, and particle characteristics by using equation (15). Although the subroutine

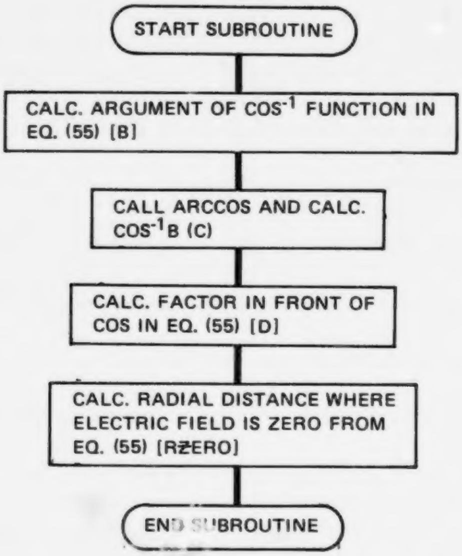

START SUBROUTINE
CALC. ARGUMENT OF COS-1 FUNCTION IN EQ. (55) [B]
CALL ARCCOS AND CALC. COS-1B (C)
CALC. FACTOR IN FRONT OF COS IN EQ. (55) [D]
CALC. RADIAL DISTANCE WHERE ELECTRIC FIELD IS ZERO FROM EQ. (55) [RZERO]
END SUBROUTINE

Figure 19. Flow chart for subroutine ZERO.

utilizes equation (15) in a straightforward manner, the programing is involved in that the values of charge at the end of each length increment due to field and diffusion charging must be kept track of independent of one another and the charging process must be incorporated into the incremental or incremental plus subincremental schemes that may be utilized in the main program. Since the free ion density and electric field change along the length of a precipitator, the values of charge due to field and diffusion charging must be saved at the end of each increment or subincrement so that they can be used as initial values for the next increment or subincrement. Also, provisions must be made to ensure that the charge acquired due to the field charging term in equation (15) does not exceed the saturation charge in any given increment or subincrement.

Figure 20 shows a detailed flow chart for this subroutine. This subroutine is called by the main program and all information which is transmitted between the main program and this subroutine is transferred through block common statements. The following is a list with descriptions of those variables which must be transmitted between the main program and this subroutine:

TDK - Temperature of the gas stream (°K).

U - Gas ion mobility (m^2/V-sec).

E - Electronic charge unit (coul).

EPSO - Permittivity of free space (coul/V·m).

BC - Boltzmann's constant (J/°K).

VAVC - Mean thermal speed of gas ions (m/sec).

NVI - Indicator which can have the values of 1 and 2. If NVI = 1, then known or measured operating voltages and currents are used in the main program and only incremental lengths are taken. If NVI = 2, then the operating voltages and currents are calculated in the main program and incremental plus subincremental lengths are taken.

I - Index which runs over incremental lengths.

SCHARG - Saturation number from field charging theory.

CHRFID - Average free ion density (#/m^3).

TIMEI - Time at the start of a given incremental or subincremental length (sec).

TIMEF - Time at the end of a given incremental or subincremental length (sec).

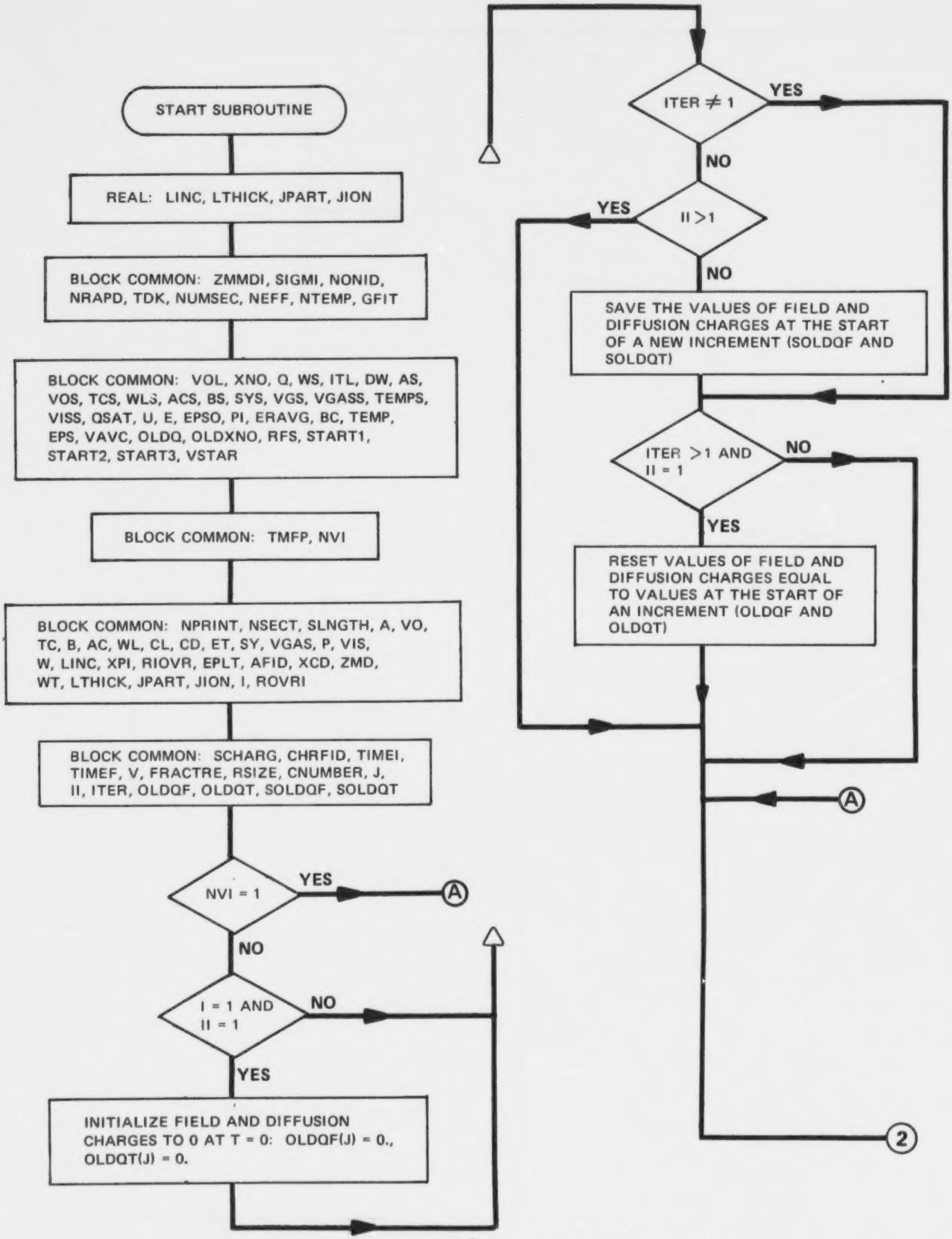
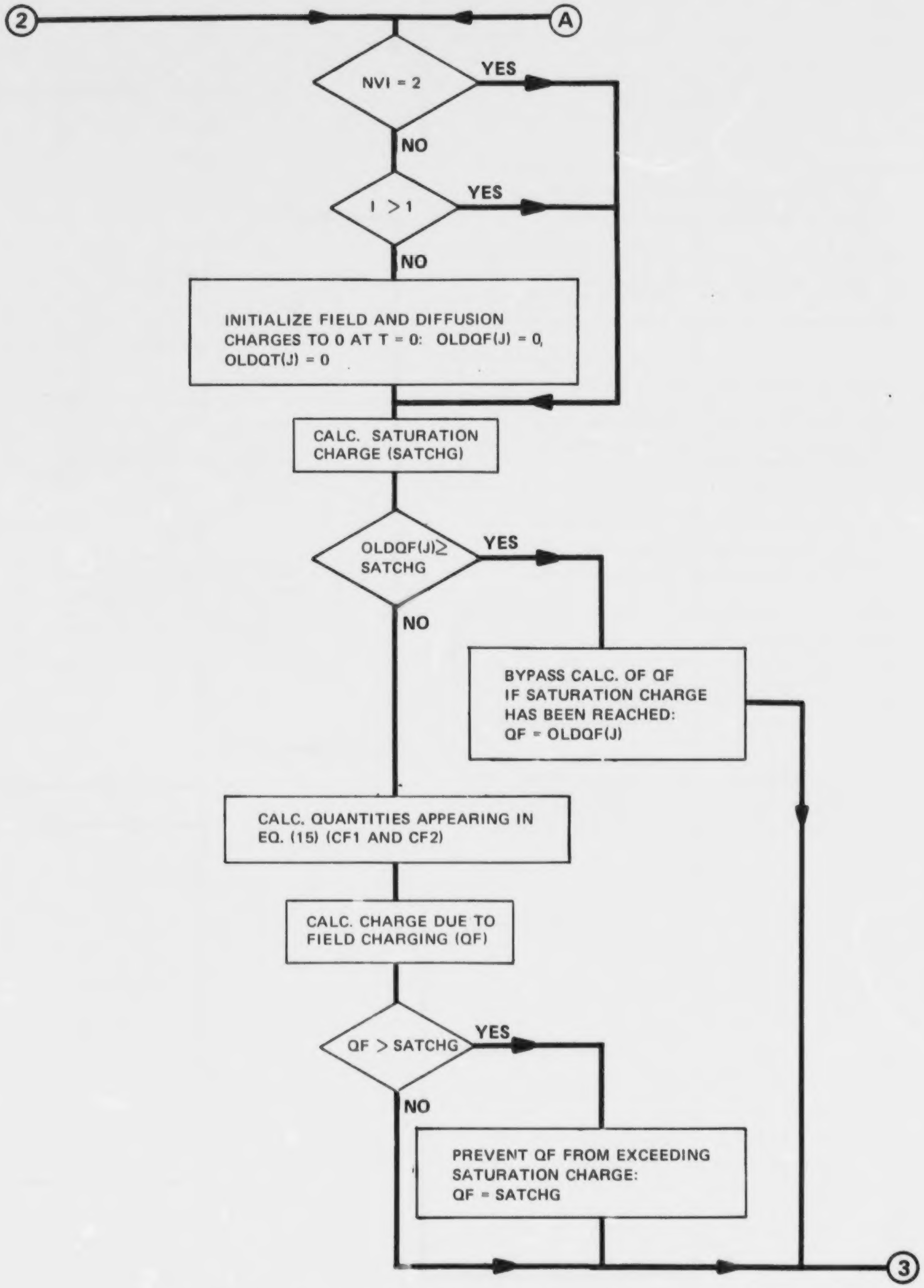

START SUBROUTINE
REAL: LINC, LTHICK, JPART, JION
BLOCK COMMON: ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT
BLOCK COMMON: VOL, XNO, Q, WS, ITL, DW, AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, QSAT, U, E, EPSO, PI, ERAVG, BC, TEMP, EPS, VAVC, OLDQ, OLDXNO, RFS, START1, START2, START3, VSTAR
BLOCK COMMON: TMFP, NVI
BLOCK COMMON: NPRINT, NSECT, SLNGTH, A, VO, TC, B, AC, WL, CL, CD, ET, SY, VGAS, P, VIS, W, LINC, XPI, RIOVR, EPLT, AFID, XCD, ZMD, WT, LTHICK, JPART, JION, I, ROVRI
BLOCK COMMON: SCHARG, CHRFID, TIMEI, TIMEF, V, FRACTRE, RSIZE, CNUMBER, J, II, ITER, OLDQF, OLDQT, SOLDQF, SOLDQT
NVI = 1
YES
Ⓐ
NO
I = 1 AND II = 1
NO
YES
INITIALIZE FIELD AND DIFFUSION CHARGES TO 0 AT T = 0: OLDQF(J) = 0., OLDQT(J) = 0.
ITER ≠ 1
YES
NO
II > 1
YES
NO
SAVE THE VALUES OF FIELD AND DIFFUSION CHARGES AT THE START OF A NEW INCREMENT (SOLDQF AND SOLDQT)
ITER > 1 AND II = 1
NO
YES
RESET VALUES OF FIELD AND DIFFUSION CHARGES EQUAL TO VALUES AT THE START OF AN INCREMENT (OLDQF AND OLDQT)
Ⓐ
②

Figure 20. Flow chart for subroutine CHGSUM (Sheet 1 of 3).



②
Ⓐ
NVI = 2
YES
NO
I > 1
YES
NO
INITIALIZE FIELD AND DIFFUSION CHARGES TO 0 AT T = 0: OLDQF(J) = 0, OLDQT(J) = 0
CALC. SATURATION CHARGE (SATCHG)
OLDQF(J) ≥ SATCHG
YES
NO
BYPASS CALC. OF QF IF SATURATION CHARGE HAS BEEN REACHED: QF = OLDQF(J)
CALC. QUANTITIES APPEARING IN EQ. (15) (CF1 AND CF2)
CALC. CHARGE DUE TO FIELD CHARGING (QF)
QF > SATCHG
YES
NO
PREVENT QF FROM EXCEEDING SATURATION CHARGE: QF = SATCHG
③

Figure 20. Flow chart for subroutine CHGSUM (Sheet 2 of 3).

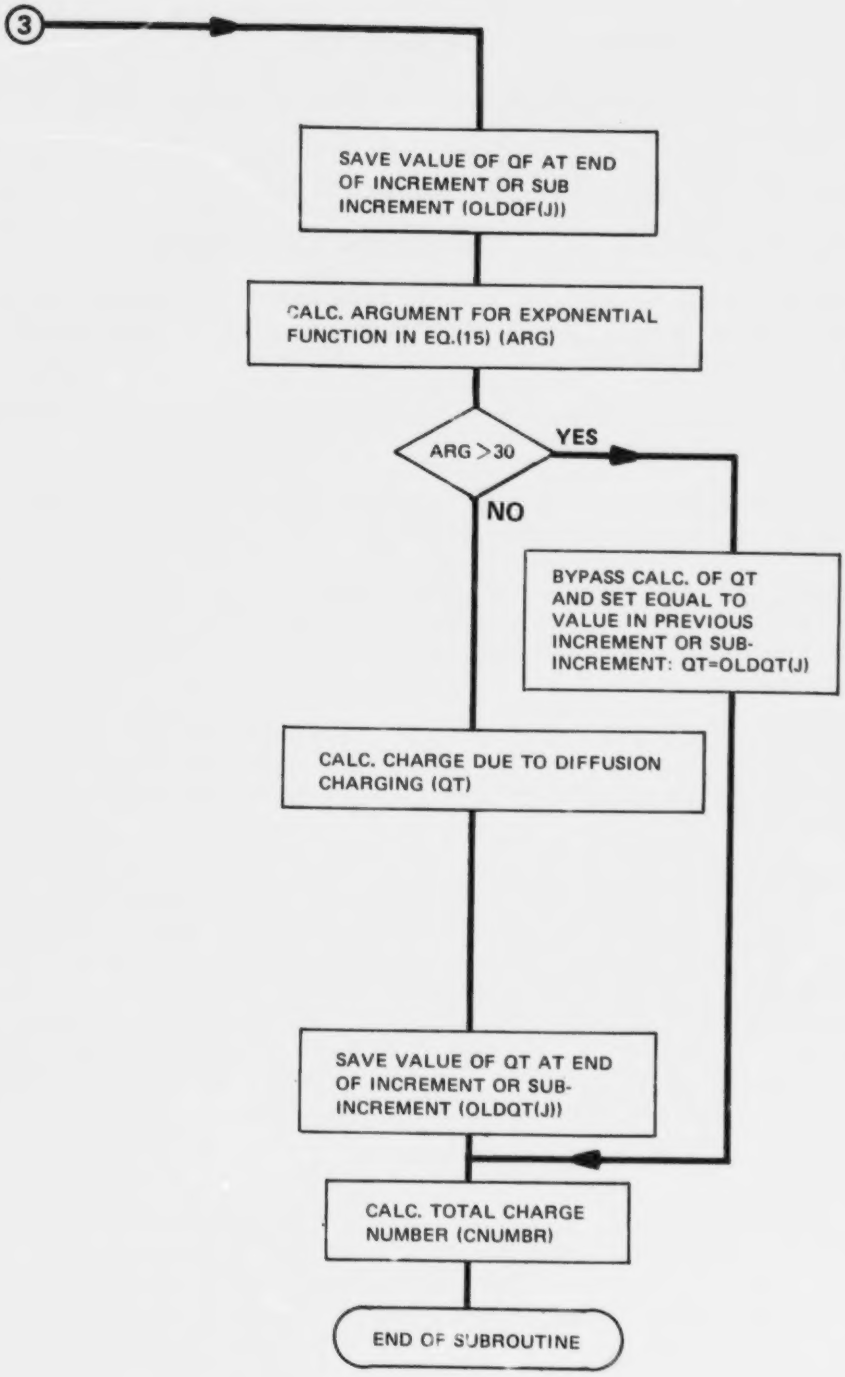

3
SAVE VALUE OF QF AT END OF INCREMENT OR SUB INCREMENT (OLDQF(J))
CALC. ARGUMENT FOR EXPONENTIAL FUNCTION IN EQ.(15) (ARG)
ARG >30
YES
NO
BYPASS CALC. OF QT AND SET EQUAL TO VALUE IN PREVIOUS INCREMENT OR SUB-INCREMENT: QT=OLDQT(J)
CALC. CHARGE DUE TO DIFFUSION CHARGING (QT)
SAVE VALUE OF QT AT END OF INCREMENT OR SUB-INCREMENT (OLDQT(J))
CALC. TOTAL CHARGE NUMBER (CNUMBR)
END OF SUBROUTINE

Figure 20. Flow chart for subroutine CHGSUM (Sheet 3 of 3).

V - Value of the quantity $[\frac{e^2}{4\pi\varepsilon_0 akT}]$.

RSIZE - Radius of a given particle size (m).

CNUMBR - Total charge number due to the sum of field and diffusional charges.

J - Index which runs over particle sizes.

II - Index which runs over subincremental lengths.

ITER - Counter that indicates which iteration is being performed over subincremental lengths in a given increment (necessary when NVI = 2).

OLDQF(J) - Value of field charge at the end of a given increment or subincrement (coul).

OLDQT(J) - Value of diffusion charge at the end of a given increment or subincrement (coul).

SOLDQF(J) - Value of field charge at the start of an increment which must be saved when NVI = 2 for the iteration procedure over subincrements in a given increment (coul).

SOLDQT(J) - Value of diffusion charge at the start of an increment which must be saved when NVI = 2 for the iteration procedure over subincrements in a given increment (coul).

Of the above variables, the values of the following must be provided by the main program: TDK, U, E, EPSO, BC, VAVC, NVI, I, SCHARG, CHRFID, TIMEI, TIMEF, V, RSIZE, J, II, and ITER. The values of the following variables are determined in the subroutine: CNUMBR, OLDQF, OLDQT, SOLDQF, and SOLDQT. In the above arrays, I, J, and II can not exceed values of 45, 20, and 30, respectively. The restrictions on I, J, and II limit the number of length increments, the number of particle size bands, and the number of subincremental lengths in a given length increment, respectively.

Subroutine ADJUST

This subroutine performs the following operations: (1) it takes the ideally-calculated effective migration velocities and adjusts them in order to account for unmodeled and nonideal effects; (2) it determines the discrete outlet mass loadings, $\Delta M/\Delta \log_{10} D$, for each particle size band for no-rap and no-rap + rap conditions and for the rapping puff; (3) it prints out detailed information of interest concerning precipitator operating conditions and performance; and (4) it prints out a table which summarizes precipitator operating conditions and performance. In order to use this subroutine, subroutines WADJST, LNDIST, LNFIT, and PRTSUM must be supplied.

The first calculation of significance which is performed is the determination of the unadjusted, ideal overall mass collection fraction (X). This quantity is determined by using the expression

$$X = \sum_i \left[{}^{(DXS)_i}/_{(ONO)_i} \right] \cdot (PCNT)_i$$

$$= \sum_i (EFESR)_i \cdot (PCNT)_i \quad , \tag{56}$$

where $(DXS)_i$ = the number of particles per cubic meter of gas in the i-th size band collected over the entire length of the precipitator under unadjusted, ideal conditions ($\#/m^3$),

$(ONO)_i$ = the number of particles per cubic meter of gas in the i-th size band in the inlet size distribution ($\#/m^3$),

$(PCNT)_i$ = the fraction by mass of the i-th particle size band in the inlet size distribution, and

$(EFESR)_i$ = the unadjusted, ideal collection fraction for the i-th particle size band over the entire length of the precipitator.

The rest of the subroutine is structured around two major loops. The outside loop runs over different "rapping puff" size distributions. The variable NRAPDC is a counter for this loop and it runs over a number of different "rapping puff" size distributions which is equal to the specified value of the variable NRAPD. The inside loop runs over different sets of nonideal conditions of gas velocity nonuniformity, gas sneakage, and particle reentrainment without rapping. The variable NONCK is a counter for this loop and it runs over a number of sets of nonideal conditions which is equal to the specified value of the variable NONID.

The initial rapping puff size distribution is fixed to be a log-normal distribution with a MMD = 6.0 μm and a $\sigma_p = 2.5$. These values correspond to the field data discussed previously and were obtained from Figure 6. Other distributions can be analyzed in the procedure discussed previously by specifying different sets of values of the MMD and σ_p in the input data to the main program. For each specified set of MMD and σ_p, the subroutine constructs a log-normal size distribution by calling subroutine LNDIST. The percentage by mass of each particle size band in the rapping puff is stored in the array RPCNT(I).

After the rapping puff size distribution is established in the outer loop, the nonideal conditions of gas velocity nonuniformity, gas sneakage, and particle reentrainment without rapping are established in the inner loop. At this point corrections are made to the unadjusted, ideal migration velocity for each particle size band in order to account for unmodeled and nonideal effects. The unadjusted, ideal migration velocity (WY) for each size band is calculated from the expression

$$WY = (VG/ATOTAL)\cdot 100\cdot \ln\,(100/(100-XEP)) \quad , \tag{57}$$

where VG = total gas volume flow rate (m^3/sec),

ATOTAL = total collection plate area (m^2), and

XEP = 100·EFESR (%).

However, if EFESR > 0.99999, WY is set equal to the value of the unadjusted, ideal migration velocity in the last increment of the precipitator.

The ideal effective migration velocities are corrected first for gas velocity nonuniformity using equation (17) and then for gas sneakage and/or particle reentrainment without rapping using equation (19). The resulting migration velocities are representative of unadjusted no-rap conditions. These unadjusted no-rap migration velocities are then corrected for unmodeled effects by using subroutine WADJST which applies the size-dependent correction factor shown in Figure 7 to each particle size band. The resulting migration velocities (WY) will be referred to as the no-rap migration velocities. No-rap collection fractions (EFESR) are determined from the no-rap migration velocities using equation (2). Again, if EFESR > 0.99999, then WY is set equal to the value of the unadjusted, ideal migration velocity in the last increment of the precipitator. The no-rap collection fractions for the different size bands are used to calculate a no-rap overall mass collection fraction using the same format as in equation (56). No-rap penetrations are also calculated.

The next set of calculations which are performed reduces the no-rap migration velocities in order to account for the effects of rapping reentrainment by using the procedure discussed previously. The total mass which is reentrained due to rapping is determined by using either equation (24) or (25). The mass collected in the last section is calculated using the no-rap overall mass collection efficiency and equation (22). The total mass which is reentrained due to rapping and the rapping puff size distribution are used to determine the number of particles in each size band which is reentrained. The number of particles reentrained is subtracted from the total number of particles collected under no-rap conditions to give the number of particles collected under no-rap + rap conditions. If the number of particles collected under no-rap + rap conditions is calculated to be a negative number, the number collected under no-rap conditions is used in its place. The number of particles in each size band collected under no-rap + rap conditions and the number of particles in each size band in the inlet size distribution are used to calculate no-rap + rap collection efficiencies, penetrations, migration velocities, and overall mass collection efficiency.

Next, several calculations are made to describe the outlet emissions under no-rap and no-rap + rap conditions and for the rapping puff. In each case, the size band penetrations are normalized and the outlet size distribution is obtained. These size distributions are then fitted to a log-normal distribution by calling subroutine LNFIT. Also, in each case, the discrete outlet mass loadings are determined by calculating $\Delta M/\Delta \log_{10} D$ for each size band.

The results of the calculations discussed above are printed out in three different sections: (1) Particle Size Range Statistics; (2) Unadjusted Migration Velocities and Efficiencies, and Discrete Outlet Mass Loadings; and (3) Summary Table of ESP Operating Parameters and Performance. The third section of printout is obtained by calling subroutine PRTSUM. The output data from the program is discussed in detail in Volume II and will not be discussed further here.

Figure 21 shows a detailed flow chart for this subroutine. This subroutine is called by the main program and all information which is transmitted between the main program, subroutine PRTSUM, and this subroutine is transferred through block common statements. The following is a list with descriptions of those variables which must be transmitted between the main program and this subroutine.

DIAM(I) - Midpoint of a given particle size band (m).

ONO(I) - Number of particles per unit volume of gas for a given particle size band entering the precipitator ($\#/m^3$).

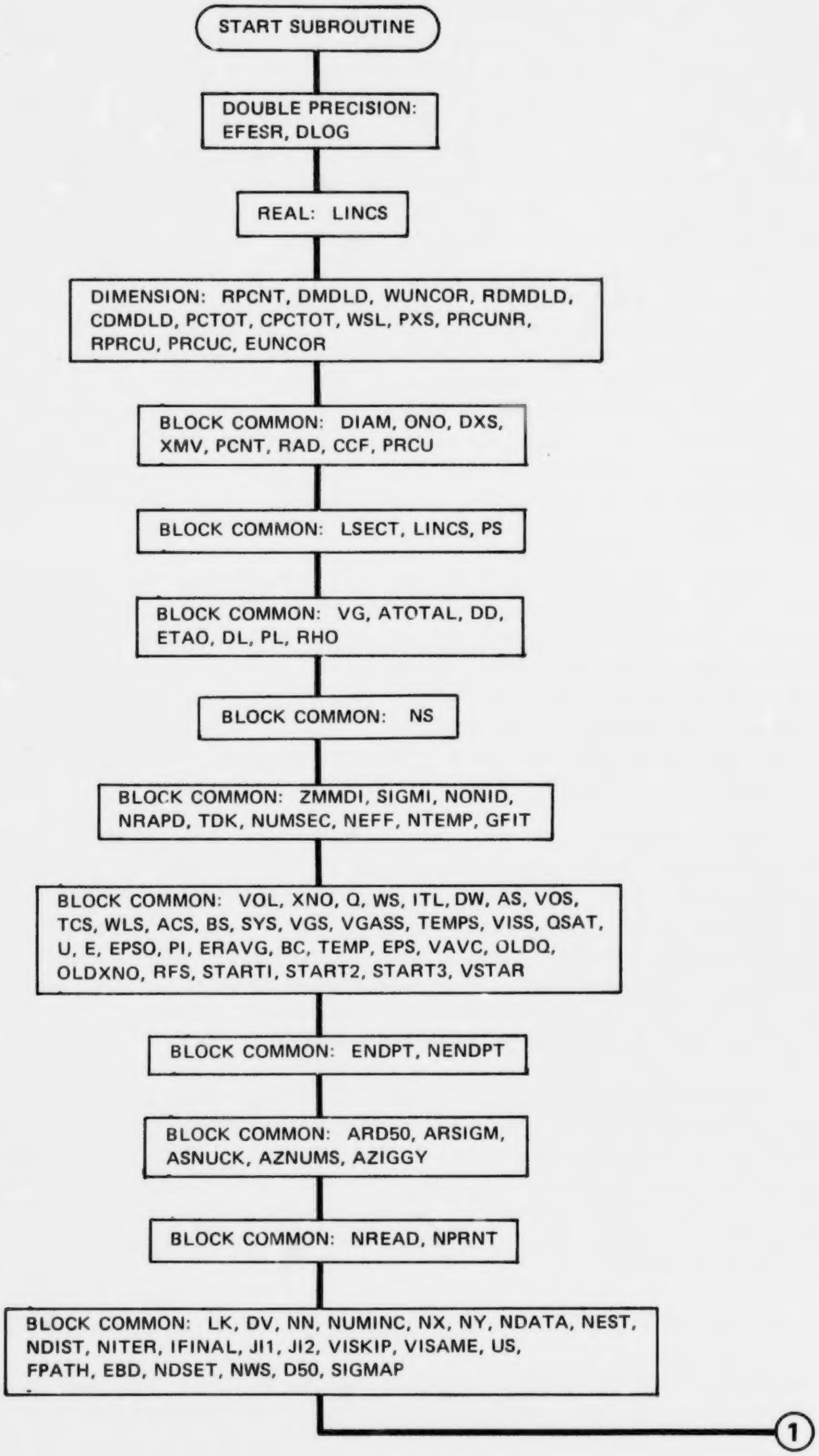

START SUBROUTINE
DOUBLE PRECISION: EFESR, DLOG
REAL: LINCS
DIMENSION: RPCNT, DMDLD, WUNCOR, RDMDLD, CDMDLD, PCTOT, CPCTOT, WSL, PXS, PRCUNR, RPRCU, PRCUC, EUNCOR
BLOCK COMMON: DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, PRCU
BLOCK COMMON: LSECT, LINCS, PS
BLOCK COMMON: VG, ATOTAL, DD, ETAO, DL, PL, RHO
BLOCK COMMON: NS
BLOCK COMMON: ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT
BLOCK COMMON: VOL, XNO, Q, WS, ITL, DW, AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, QSAT, U, E, EPSO, PI, ERAVG, BC, TEMP, EPS, VAVC, OLDQ, OLDXNO, RFS, STARTI, START2, START3, VSTAR
BLOCK COMMON: ENDPT, NENDPT
BLOCK COMMON: ARD50, ARSIGM, ASNUCK, AZNUMS, AZIGGY
BLOCK COMMON: NREAD, NPRNT
BLOCK COMMON: LK, DV, NN, NUMINC, NX, NY, NDATA, NEST, NDIST, NITER, IFINAL, JI1, JI2, VISKIP, VISAME, US, FPATH, EBD, NDSET, NWS, D50, SIGMAP
1

Figure 21. Flow chart for subroutine ADJUST (Sheet 1 of 12).

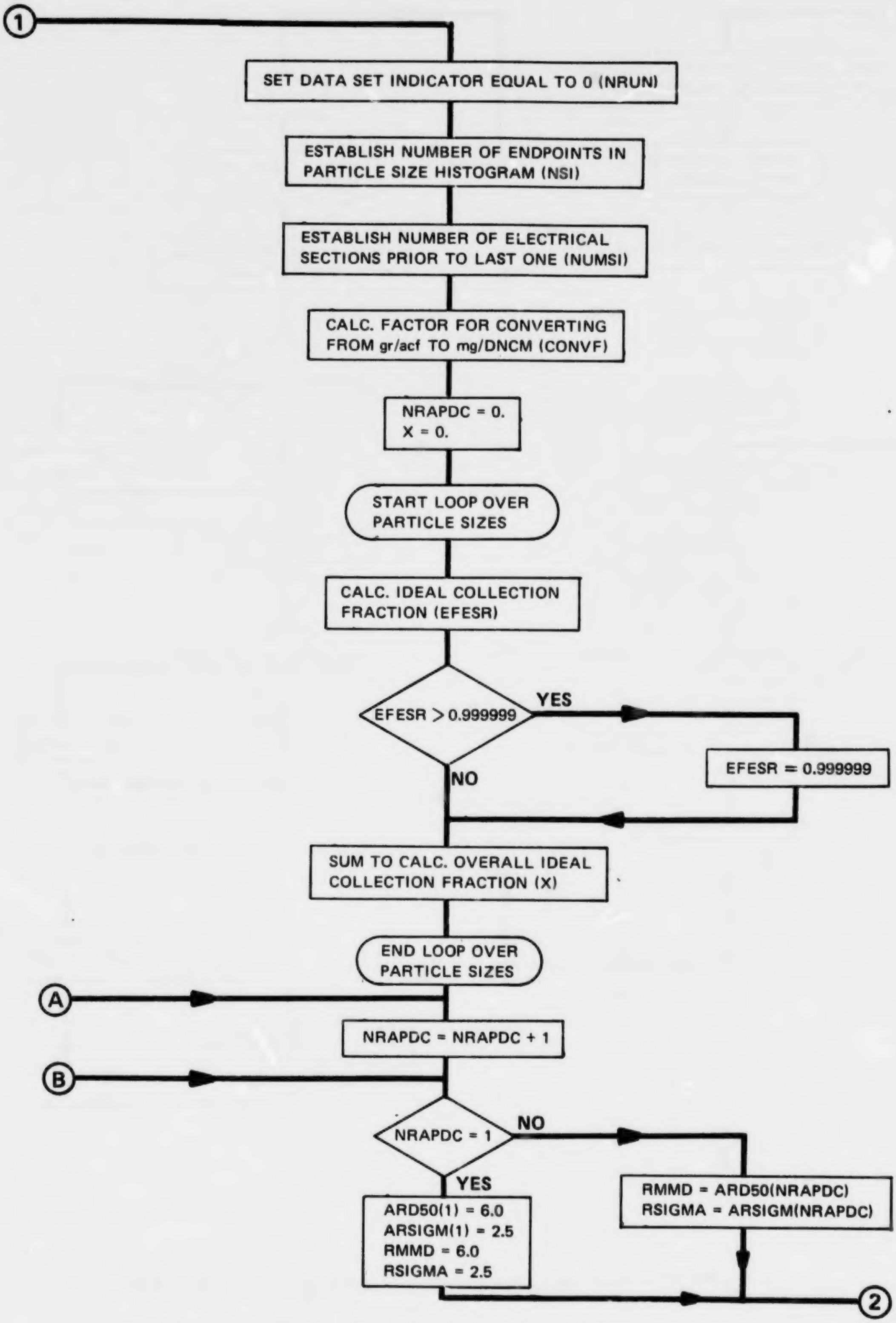

①
SET DATA SET INDICATOR EQUAL TO 0 (NRUN)
ESTABLISH NUMBER OF ENDPOINTS IN PARTICLE SIZE HISTOGRAM (NSI)
ESTABLISH NUMBER OF ELECTRICAL SECTIONS PRIOR TO LAST ONE (NUMSI)
CALC. FACTOR FOR CONVERTING FROM gr/acf TO mg/DNCM (CONVF)
NRAPDC = 0.
X = 0.
START LOOP OVER PARTICLE SIZES
CALC. IDEAL COLLECTION FRACTION (EFESR)
EFESR > 0.999999
YES
EFESR = 0.999999
NO
SUM TO CALC. OVERALL IDEAL COLLECTION FRACTION (X)
END LOOP OVER PARTICLE SIZES
Ⓐ
NRAPDC = NRAPDC + 1
Ⓑ
NRAPDC = 1
NO
RMMD = ARD50(NRAPDC)
RSIGMA = ARSIGM(NRAPDC)
YES
ARD50(1) = 6.0
ARSIGM(1) = 2.5
RMMD = 6.0
RSIGMA = 2.5
②

Figure 21. Flow chart for subroutine ADJUST (Sheet 2 of 12).

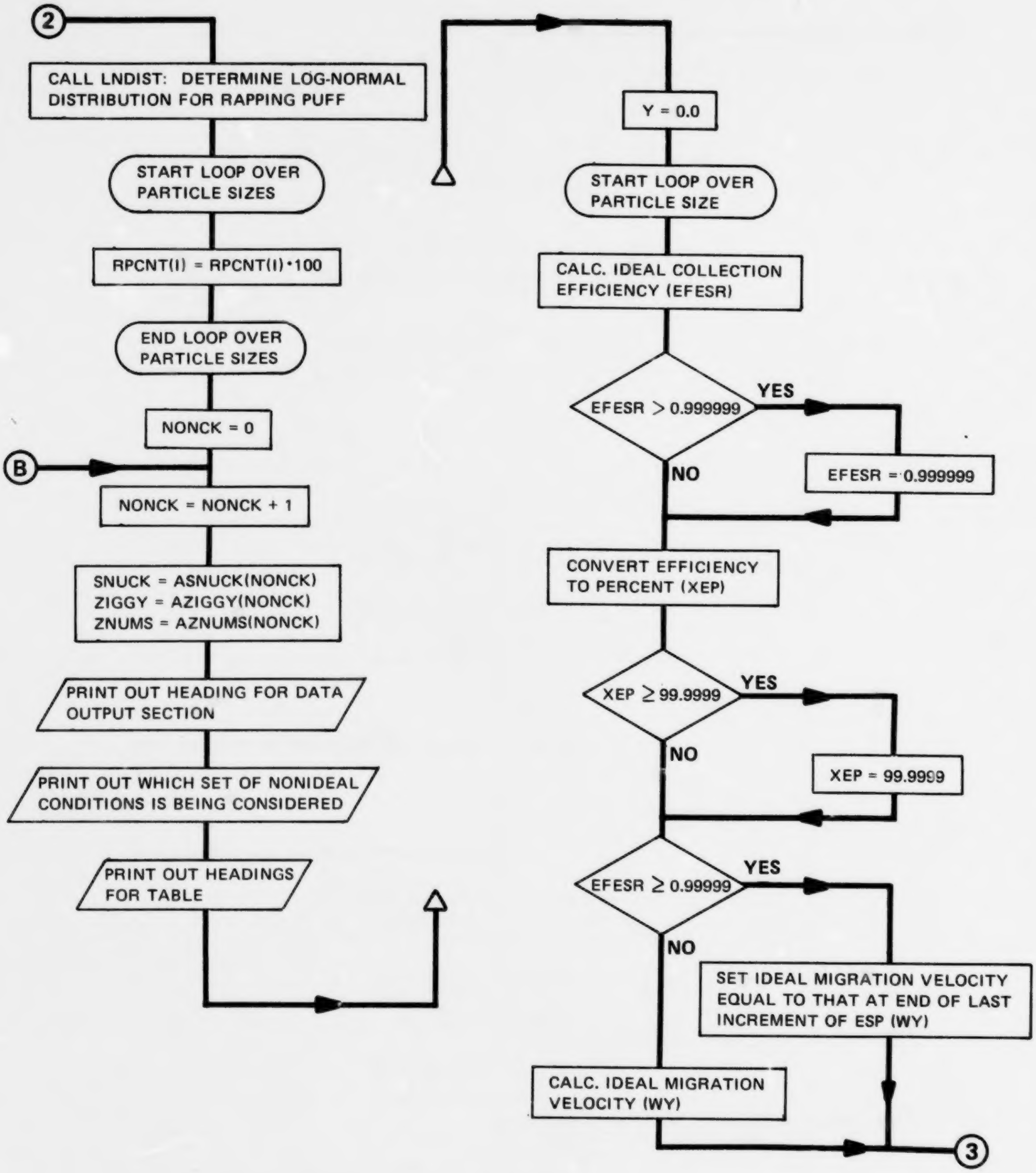

②
CALL LNDIST: DETERMINE LOG-NORMAL DISTRIBUTION FOR RAPPING PUFF
START LOOP OVER PARTICLE SIZES
RPCNT(I) = RPCNT(I)·100
END LOOP OVER PARTICLE SIZES
NONCK = 0
B
NONCK = NONCK + 1
SNUCK = ASNUCK(NONCK)
ZIGGY = AZIGGY(NONCK)
ZNUMS = AZNUMS(NONCK)
PRINT OUT HEADING FOR DATA OUTPUT SECTION
PRINT OUT WHICH SET OF NONIDEAL CONDITIONS IS BEING CONSIDERED
PRINT OUT HEADINGS FOR TABLE
Y = 0.0
START LOOP OVER PARTICLE SIZE
CALC. IDEAL COLLECTION EFFICIENCY (EFESR)
EFESR > 0.999999
YES
NO
EFESR = 0.999999
CONVERT EFFICIENCY TO PERCENT (XEP)
XEP ≥ 99.9999
YES
NO
XEP = 99.9999
EFESR ≥ 0.99999
YES
NO
SET IDEAL MIGRATION VELOCITY EQUAL TO THAT AT END OF LAST INCREMENT OF ESP (WY)
CALC. IDEAL MIGRATION VELOCITY (WY)
③

Figure 21. Flow chart for subroutine ADJUST (Sheet 3 of 12).

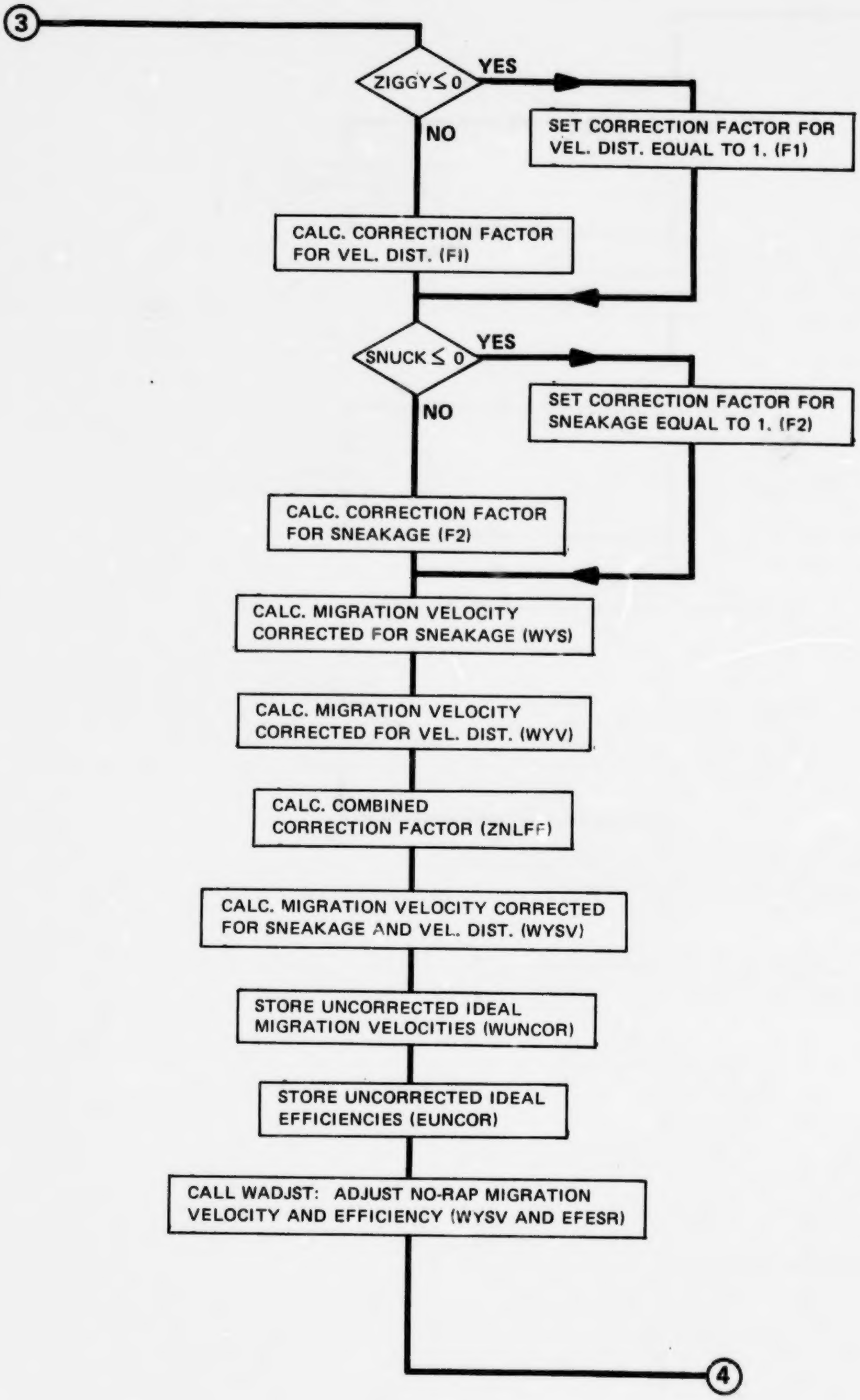

③
ZIGGY ≤ 0
YES
NO
SET CORRECTION FACTOR FOR VEL. DIST. EQUAL TO 1. (F1)
CALC. CORRECTION FACTOR FOR VEL. DIST. (FI)
SNUCK ≤ 0
YES
NO
SET CORRECTION FACTOR FOR SNEAKAGE EQUAL TO 1. (F2)
CALC. CORRECTION FACTOR FOR SNEAKAGE (F2)
CALC. MIGRATION VELOCITY CORRECTED FOR SNEAKAGE (WYS)
CALC. MIGRATION VELOCITY CORRECTED FOR VEL. DIST. (WYV)
CALC. COMBINED CORRECTION FACTOR (ZNLFF)
CALC. MIGRATION VELOCITY CORRECTED FOR SNEAKAGE AND VEL. DIST. (WYSV)
STORE UNCORRECTED IDEAL MIGRATION VELOCITIES (WUNCOR)
STORE UNCORRECTED IDEAL EFFICIENCIES (EUNCOR)
CALL WADJST: ADJUST NO-RAP MIGRATION VELOCITY AND EFFICIENCY (WYSV AND EFESR)
④

Figure 21. Flow chart for subroutine ADJUST (Sheet 4 of 12).

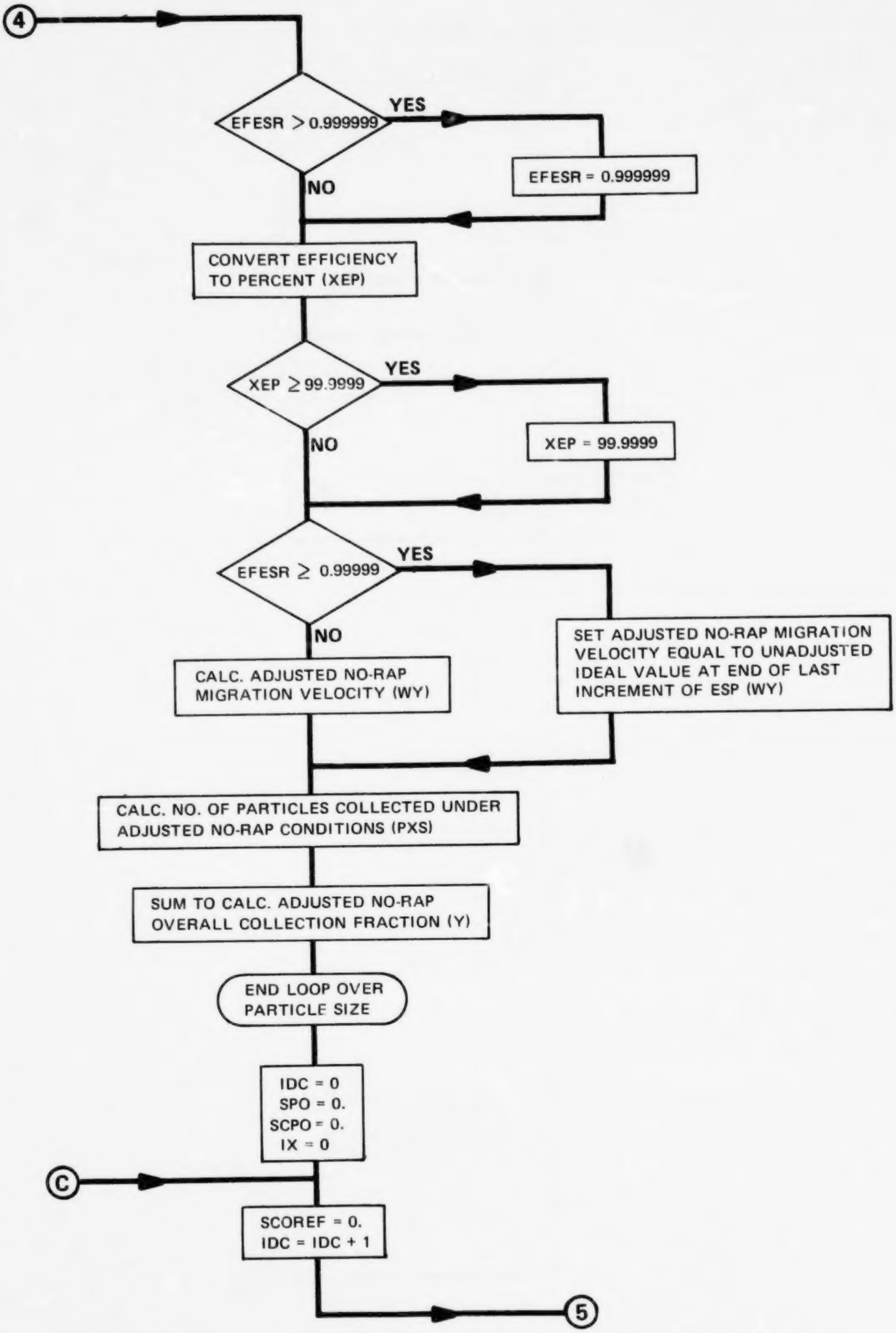

4
EFESR > 0.999999
YES
NO
EFESR = 0.999999
CONVERT EFFICIENCY TO PERCENT (XEP)
XEP ≥ 99.9999
YES
NO
XEP = 99.9999
EFESR ≥ 0.99999
YES
NO
CALC. ADJUSTED NO-RAP MIGRATION VELOCITY (WY)
SET ADJUSTED NO-RAP MIGRATION VELOCITY EQUAL TO UNADJUSTED IDEAL VALUE AT END OF LAST INCREMENT OF ESP (WY)
CALC. NO. OF PARTICLES COLLECTED UNDER ADJUSTED NO-RAP CONDITIONS (PXS)
SUM TO CALC. ADJUSTED NO-RAP OVERALL COLLECTION FRACTION (Y)
END LOOP OVER PARTICLE SIZE
IDC = 0
SPO = 0.
SCPO = 0.
IX = 0
C
SCOREF = 0.
IDC = IDC + 1
5

Figure 21. Flow chart for subroutine ADJUST (Sheet 5 of 12).

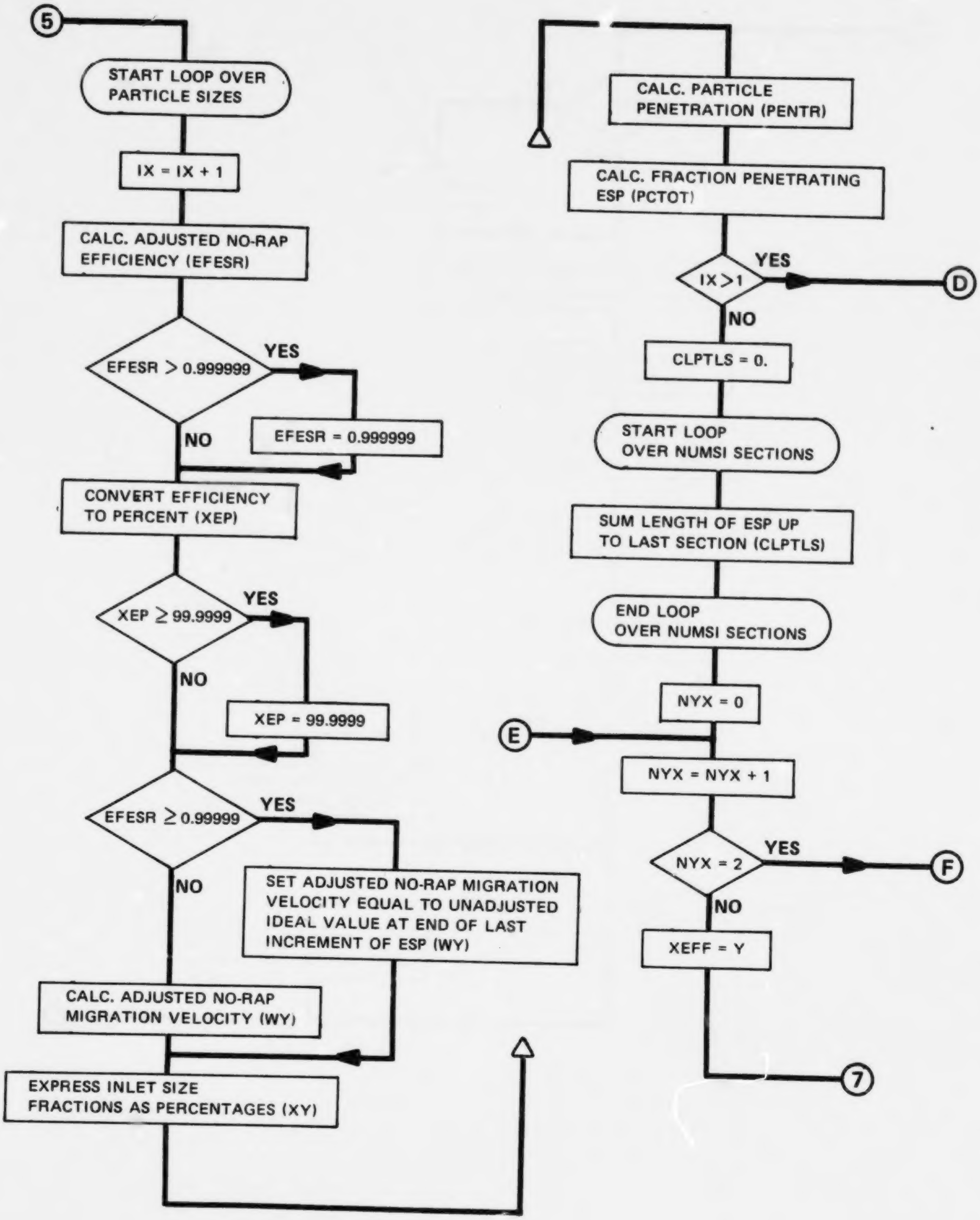

5
START LOOP OVER PARTICLE SIZES
IX = IX + 1
CALC. ADJUSTED NO-RAP EFFICIENCY (EFESR)
EFESR > 0.999999
YES
NO
EFESR = 0.999999
CONVERT EFFICIENCY TO PERCENT (XEP)
XEP ≥ 99.9999
YES
NO
XEP = 99.9999
EFESR ≥ 0.99999
YES
NO
SET ADJUSTED NO-RAP MIGRATION VELOCITY EQUAL TO UNADJUSTED IDEAL VALUE AT END OF LAST INCREMENT OF ESP (WY)
CALC. ADJUSTED NO-RAP MIGRATION VELOCITY (WY)
EXPRESS INLET SIZE FRACTIONS AS PERCENTAGES (XY)
CALC. PARTICLE PENETRATION (PENTR)
CALC. FRACTION PENETRATING ESP (PCTOT)
IX>1
YES
D
NO
CLPTLS = 0.
START LOOP OVER NUMSI SECTIONS
SUM LENGTH OF ESP UP TO LAST SECTION (CLPTLS)
END LOOP OVER NUMSI SECTIONS
NYX = 0
E
NYX = NYX + 1
NYX = 2
YES
F
NO
XEFF = Y
7

Figure 21. Flow chart for subroutine ADJUST (Sheet 6 of 12).

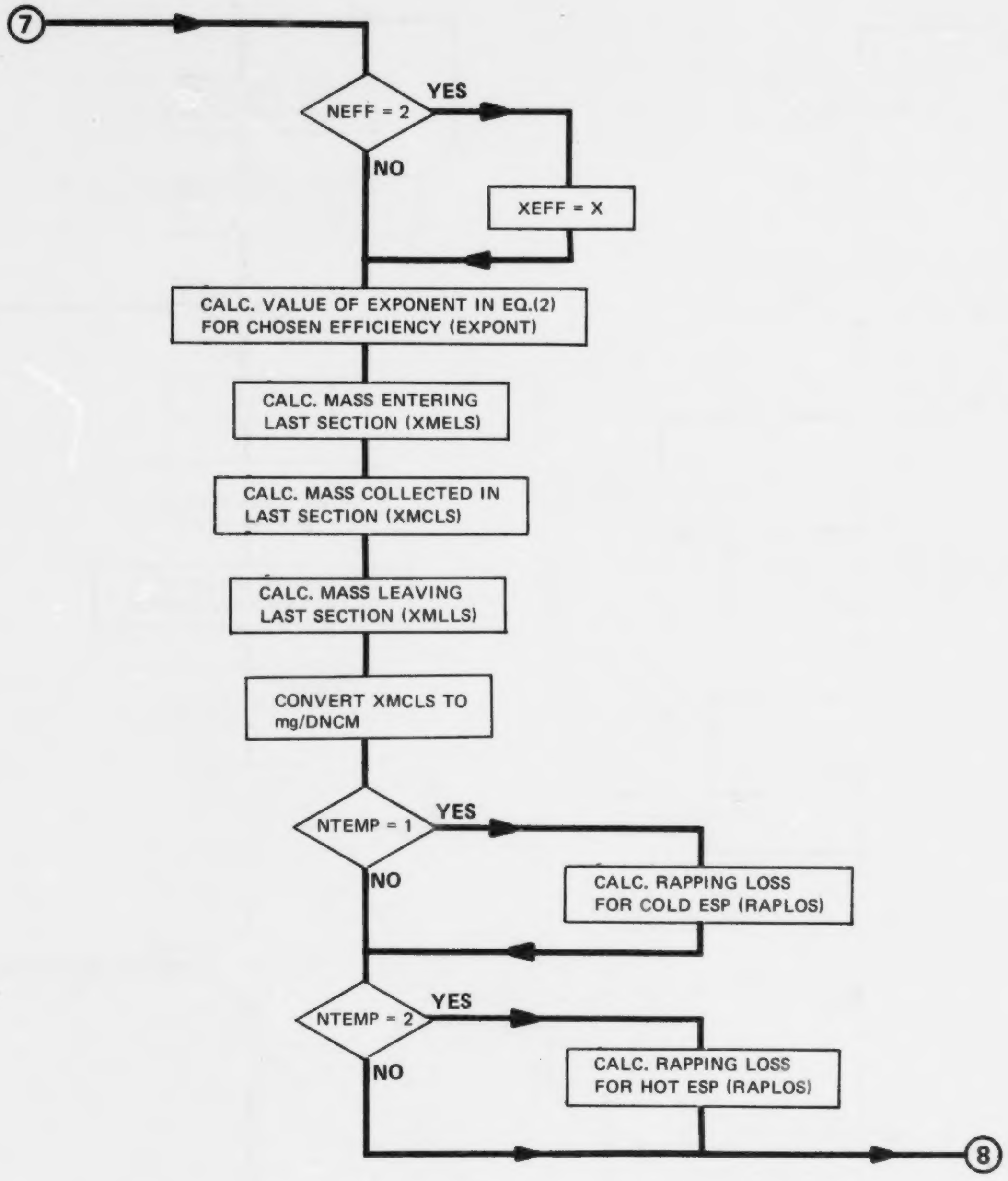

7
NEFF = 2
YES
NO
XEFF = X
CALC. VALUE OF EXPONENT IN EQ.(2) FOR CHOSEN EFFICIENCY (EXPONT)
CALC. MASS ENTERING LAST SECTION (XMELS)
CALC. MASS COLLECTED IN LAST SECTION (XMCLS)
CALC. MASS LEAVING LAST SECTION (XMLLS)
CONVERT XMCLS TO mg/DNCM
NTEMP = 1
YES
NO
CALC. RAPPING LOSS FOR COLD ESP (RAPLOS)
NTEMP = 2
YES
NO
CALC. RAPPING LOSS FOR HOT ESP (RAPLOS)
8

Figure 21. Flow chart for subroutine ADJUST (Sheet 7 of 12).

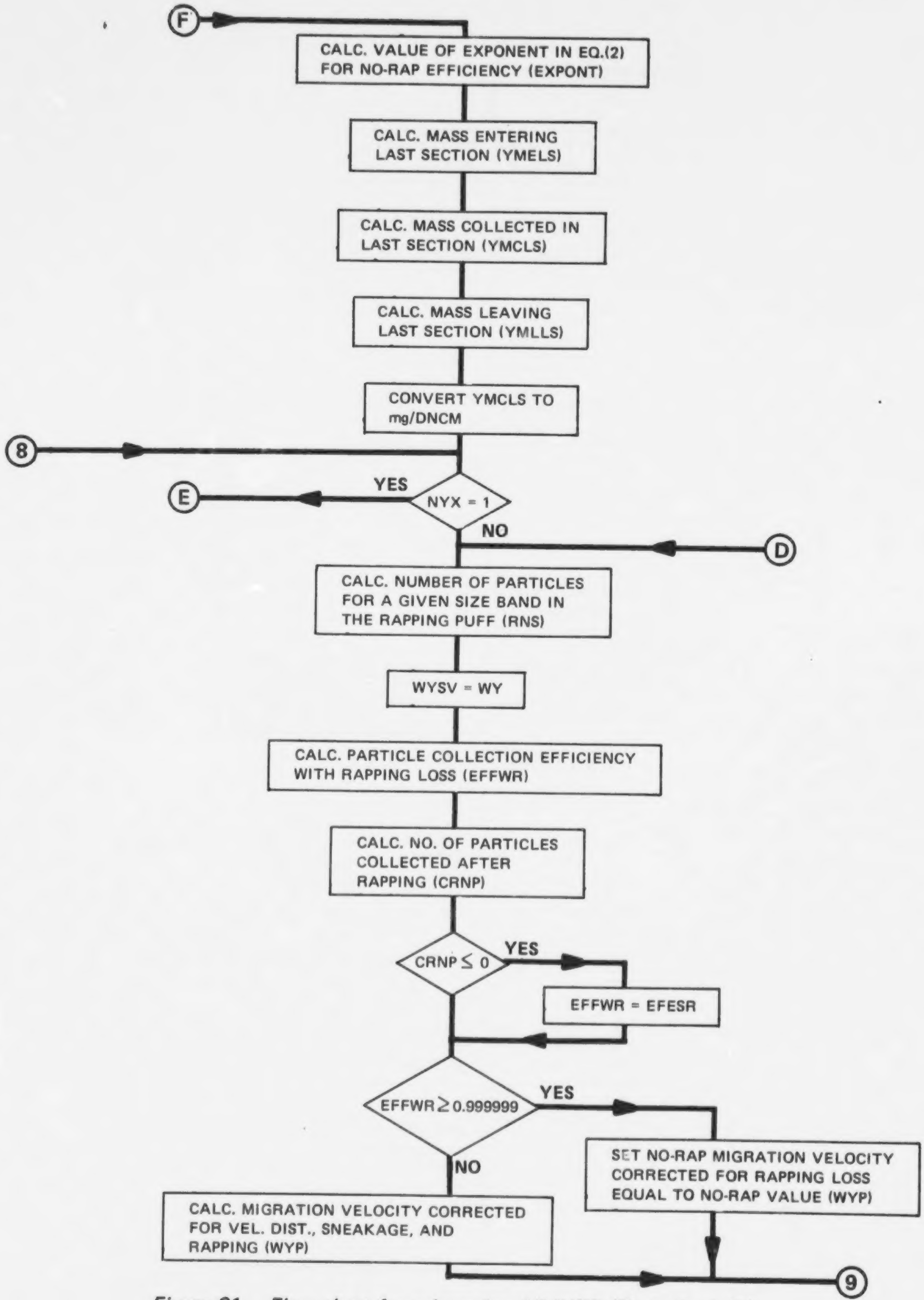

F
CALC. VALUE OF EXPONENT IN EQ.(2) FOR NO-RAP EFFICIENCY (EXPONT)
CALC. MASS ENTERING LAST SECTION (YMELS)
CALC. MASS COLLECTED IN LAST SECTION (YMCLS)
CALC. MASS LEAVING LAST SECTION (YMLLS)
CONVERT YMCLS TO mg/DNCM
8
YES
E
NYX = 1
NO
D
CALC. NUMBER OF PARTICLES FOR A GIVEN SIZE BAND IN THE RAPPING PUFF (RNS)
WYSV = WY
CALC. PARTICLE COLLECTION EFFICIENCY WITH RAPPING LOSS (EFFWR)
CALC. NO. OF PARTICLES COLLECTED AFTER RAPPING (CRNP)
CRNP ≤ 0
YES
EFFWR = EFESR
EFFWR ≥ 0.999999
YES
SET NO-RAP MIGRATION VELOCITY CORRECTED FOR RAPPING LOSS EQUAL TO NO-RAP VALUE (WYP)
NO
CALC. MIGRATION VELOCITY CORRECTED FOR VEL. DIST., SNEAKAGE, AND RAPPING (WYP)
9

Figure 21. Flow chart for subroutine ADJUST (Sheet 8 of 12).

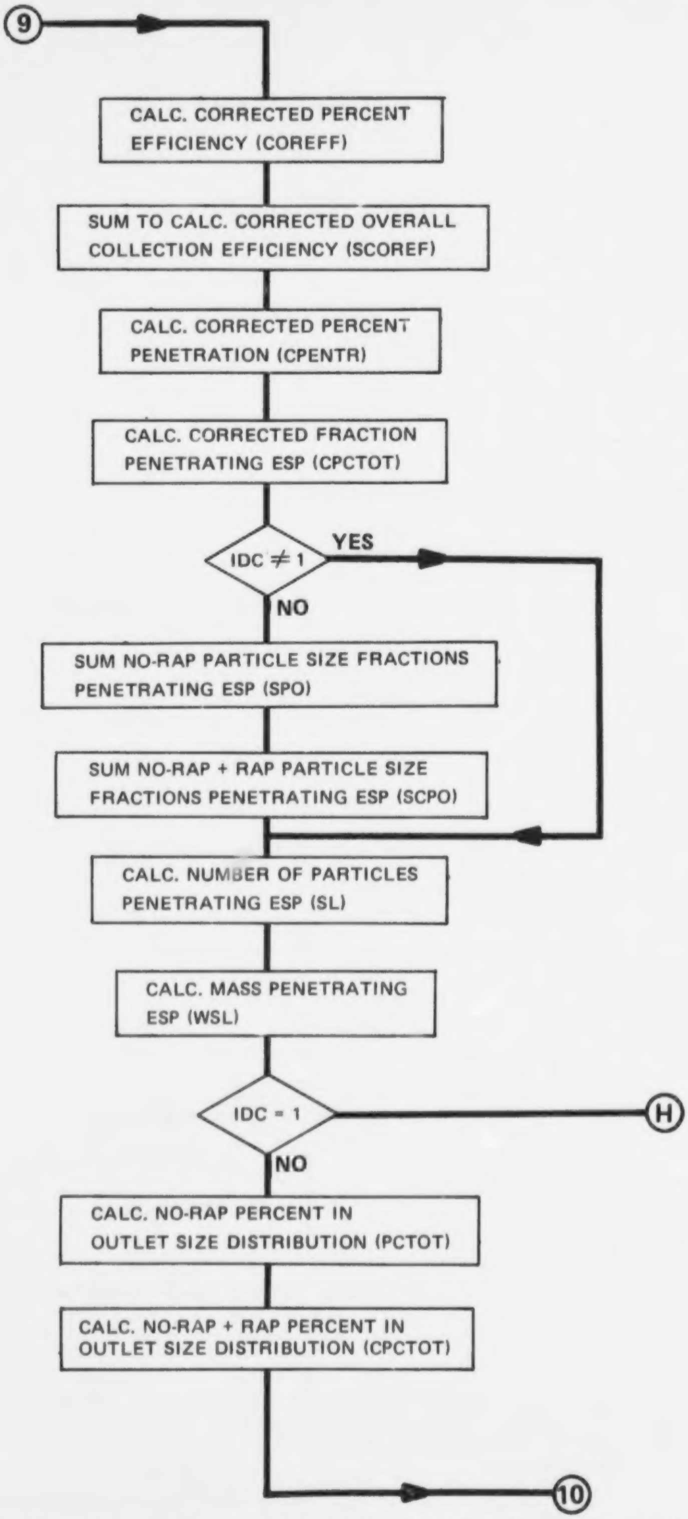

9
CALC. CORRECTED PERCENT EFFICIENCY (COREFF)
SUM TO CALC. CORRECTED OVERALL COLLECTION EFFICIENCY (SCOREF)
CALC. CORRECTED PERCENT PENETRATION (CPENTR)
CALC. CORRECTED FRACTION PENETRATING ESP (CPCTOT)
IDC ≠ 1
YES
NO
SUM NO-RAP PARTICLE SIZE FRACTIONS PENETRATING ESP (SPO)
SUM NO-RAP + RAP PARTICLE SIZE FRACTIONS PENETRATING ESP (SCPO)
CALC. NUMBER OF PARTICLES PENETRATING ESP (SL)
CALC. MASS PENETRATING ESP (WSL)
IDC = 1
H
NO
CALC. NO-RAP PERCENT IN OUTLET SIZE DISTRIBUTION (PCTOT)
CALC. NO-RAP + RAP PERCENT IN OUTLET SIZE DISTRIBUTION (CPCTOT)
10

Figure 21. Flow chart for subroutine ADJUST (Sheet 9 of 12)

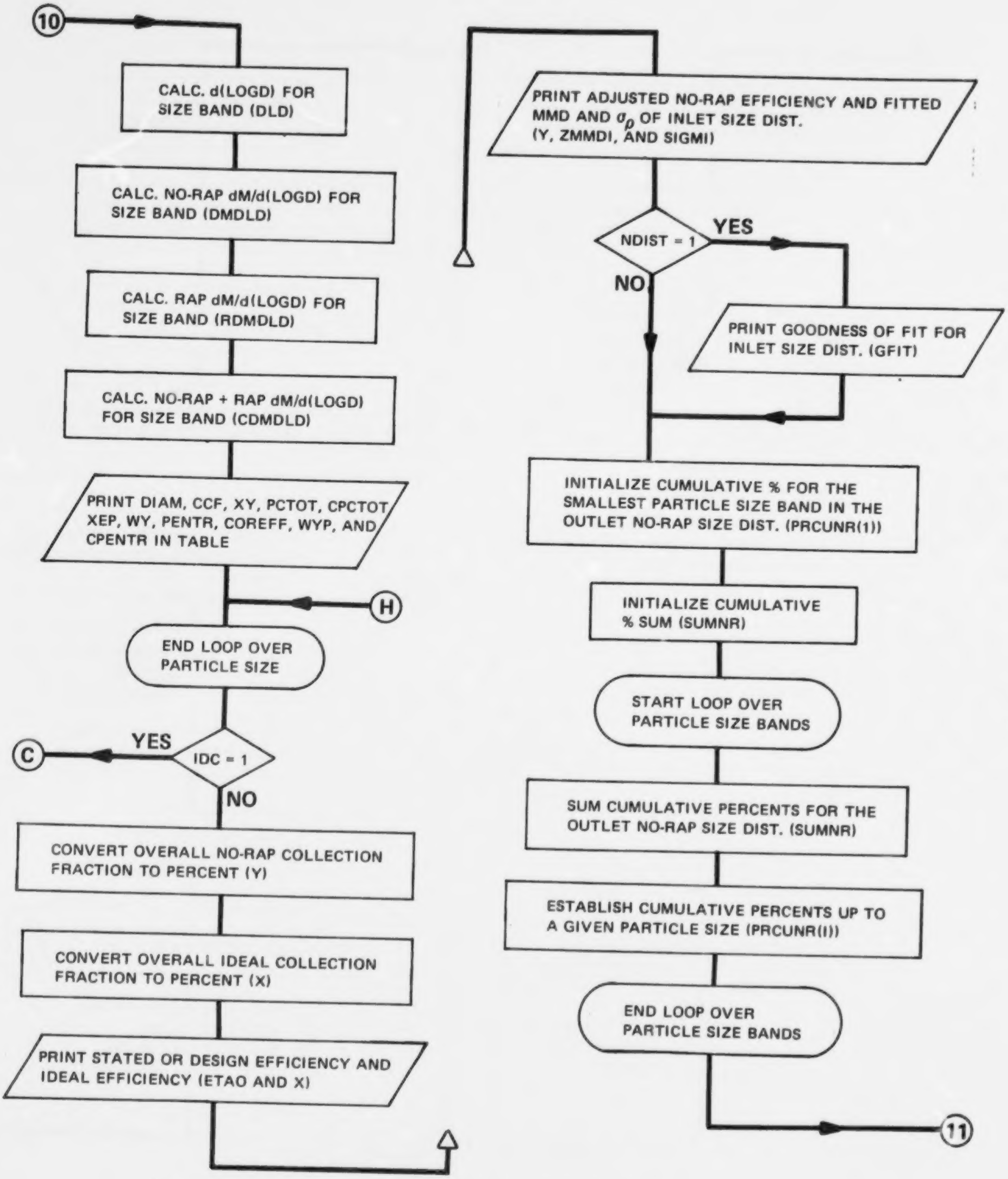

10
CALC. d(LOGD) FOR SIZE BAND (DLD)
CALC. NO-RAP dM/d(LOGD) FOR SIZE BAND (DMDLD)
CALC. RAP dM/d(LOGD) FOR SIZE BAND (RDMDLD)
CALC. NO-RAP + RAP dM/d(LOGD) FOR SIZE BAND (CDMDLD)
PRINT DIAM, CCF, XY, PCTOT, CPCTOT, XEP, WY, PENTR, COREFF, WYP, AND CPENTR IN TABLE
H
END LOOP OVER PARTICLE SIZE
C
YES
IDC = 1
NO
CONVERT OVERALL NO-RAP COLLECTION FRACTION TO PERCENT (Y)
CONVERT OVERALL IDEAL COLLECTION FRACTION TO PERCENT (X)
PRINT STATED OR DESIGN EFFICIENCY AND IDEAL EFFICIENCY (ETAO AND X)
PRINT ADJUSTED NO-RAP EFFICIENCY AND FITTED MMD AND σ_p OF INLET SIZE DIST. (Y, ZMMDI, AND SIGMI)
NDIST = 1
YES
NO
PRINT GOODNESS OF FIT FOR INLET SIZE DIST. (GFIT)
INITIALIZE CUMULATIVE % FOR THE SMALLEST PARTICLE SIZE BAND IN THE OUTLET NO-RAP SIZE DIST. (PRCUNR(1))
INITIALIZE CUMULATIVE % SUM (SUMNR)
START LOOP OVER PARTICLE SIZE BANDS
SUM CUMULATIVE PERCENTS FOR THE OUTLET NO-RAP SIZE DIST. (SUMNR)
ESTABLISH CUMULATIVE PERCENTS UP TO A GIVEN PARTICLE SIZE (PRCUNR(I))
END LOOP OVER PARTICLE SIZE BANDS
11

Figure 21. Flow chart for subroutine ADJUST (Sheet 10 of 12).

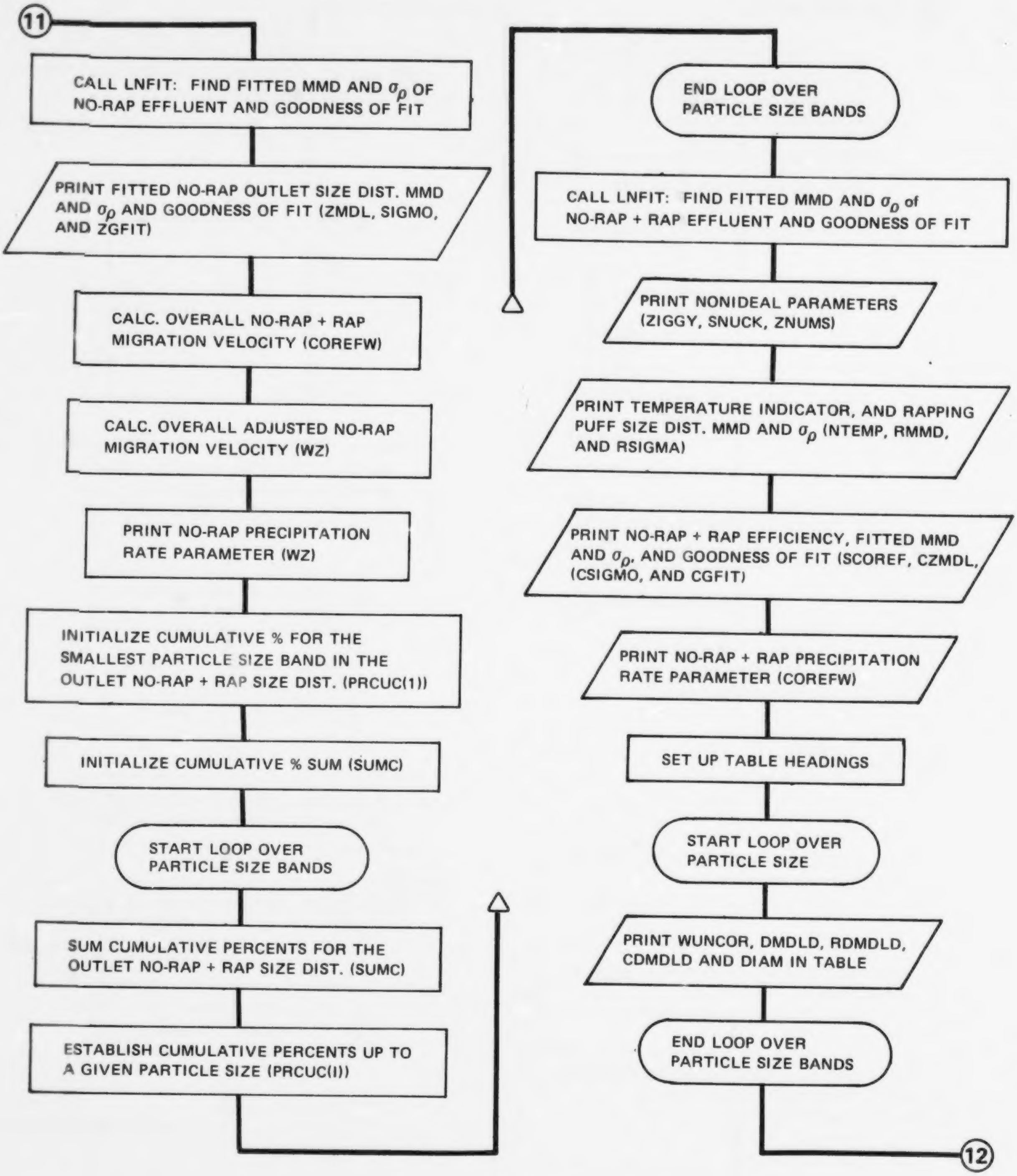

11
CALL LNFIT: FIND FITTED MMD AND σ_ρ OF NO-RAP EFFLUENT AND GOODNESS OF FIT
PRINT FITTED NO-RAP OUTLET SIZE DIST. MMD AND σ_ρ AND GOODNESS OF FIT (ZMDL, SIGMO, AND ZGFIT)
CALC. OVERALL NO-RAP + RAP MIGRATION VELOCITY (COREFW)
CALC. OVERALL ADJUSTED NO-RAP MIGRATION VELOCITY (WZ)
PRINT NO-RAP PRECIPITATION RATE PARAMETER (WZ)
INITIALIZE CUMULATIVE % FOR THE SMALLEST PARTICLE SIZE BAND IN THE OUTLET NO-RAP + RAP SIZE DIST. (PRCUC(1))
INITIALIZE CUMULATIVE % SUM (SUMC)
START LOOP OVER PARTICLE SIZE BANDS
SUM CUMULATIVE PERCENTS FOR THE OUTLET NO-RAP + RAP SIZE DIST. (SUMC)
ESTABLISH CUMULATIVE PERCENTS UP TO A GIVEN PARTICLE SIZE (PRCUC(I))
END LOOP OVER PARTICLE SIZE BANDS
CALL LNFIT: FIND FITTED MMD AND σ_ρ of NO-RAP + RAP EFFLUENT AND GOODNESS OF FIT
PRINT NONIDEAL PARAMETERS (ZIGGY, SNUCK, ZNUMS)
PRINT TEMPERATURE INDICATOR, AND RAPPING PUFF SIZE DIST. MMD AND σ_ρ (NTEMP, RMMD, AND RSIGMA)
PRINT NO-RAP + RAP EFFICIENCY, FITTED MMD AND σ_ρ, AND GOODNESS OF FIT (SCOREF, CZMDL, (CSIGMO, AND CGFIT)
PRINT NO-RAP + RAP PRECIPITATION RATE PARAMETER (COREFW)
SET UP TABLE HEADINGS
START LOOP OVER PARTICLE SIZE
PRINT WUNCOR, DMDLD, RDMDLD, CDMDLD AND DIAM IN TABLE
END LOOP OVER PARTICLE SIZE BANDS
12

Figure 21. Flow chart for subroutine ADJUST (Sheet 11 of 12).

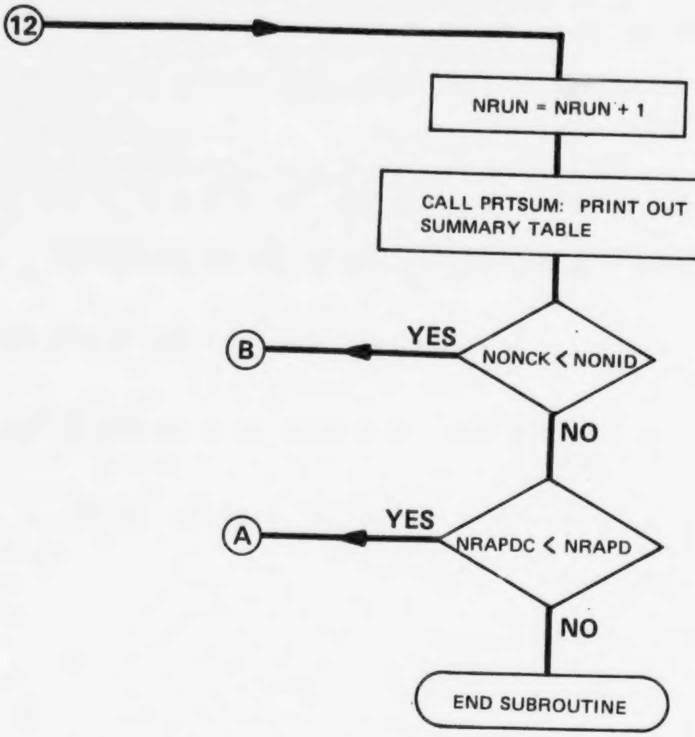

12
NRUN = NRUN + 1
CALL PRTSUM: PRINT OUT SUMMARY TABLE
YES
B
NONCK < NONID
NO
YES
A
NRAPDC < NRAPD
NO
END SUBROUTINE

Figure 21. Flow chart for subroutine ADJUST (Sheet 12 of 12).

DXS(I) - Number of particles per unit volume of gas for a given particle size band which are removed from the gas stream under unadjusted, ideal conditions (#/m^3).

XMV(I) - Unadjusted, ideal migration velocity for a given particle size band (cm/sec).

PCNT(I) - Fraction by mass of a given particle size band in the inlet particle size distribution.

CCF(I) - Cunningham correction factor for a given particle size band.

LSECT(J) - Number of increments to be taken in a given electrical section.

LINCS(J) - Incremental length size to be taken in a given electrical section (ft).

PS(J) - Gas pressure in a given electrical section (atm).

VG - Gas volume flow rate (m^3/sec).

ATOTAL - Total collection plate area (m^2).

DD - Mass density of the particles (kg/m^3).

ETAO - Estimated or design efficiency (%).

DL - Inlet mass loading (kg/m^3).

PL - Total electrical length of the precipitator (m).

RHO - Resistivity of collected particulate layer (ohm-m).

NS - Number of size bands in inlet particle size histogram.

ZMMDI - Fitted mass median diameter of the inlet particle size distribution (m).

SIGMI - Fitted geometric standard deviation of the inlet particle size distribution.

NONID - Total number of sets of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered.

NRAPD - Total number of rapping puff size distributions to be considered.

TDK - Temperature of the gas stream (°K).

NUMSEC - Number of electrical sections in the direction of gas flow.

NEFF - Indicator which can have the values of 1 and 2. If NEFF = 1, then the total mass reentrained at the outlet due to rapping is determined from the mass collected in the last field under adjusted no-rap conditions. If NEFF = 2, then the total mass reentrained at the outlet due to rapping is determined from the mass which would be collected in the last field under unadjusted, ideal conditions.

NTEMP - Indicator which can have the values of 1 and 2. If NTEMP = 1, then the mass reentrained due to rapping is calculated based on equation (24) for a cold-side precipitator. If NTEMP = 2, then the mass reentrained due to rapping is calculated based on equation (25) for a hot-side precipitator.

GFIT - Log-normal goodness of fit parameter for the fitted inlet particle size distribution.

VOS(J) - Applied voltage in a given electrical section (V).

TCS(J) - Total current in a given electrical section (A).

ENDPT(K) - Endpoints of the particle size band intervals in the inlet particle size histogram (μm).

NENDPT - Number of endpoints in the inlet particle size distribution histogram.

ARD50(L) - Specified mass median diameter used to describe a log-normal particle size distribution for the rapping puff (μm).

ARSIGM(L) - Specified geometric standard deviation used to describe a log-normal particle size distribution for the rapping puff.

ASNUCK(M) - Specified fraction of gas flow which bypasses the electrified region in each baffled stage of the precipitator and/or fraction of the mass collected in each stage of the precipitator which is reentrained due to factors other than rapping.

AZNUMS(M) - Specified number of baffled stages in the precipitator.

AZIGGY(M) - Specified normalized standard deviation of the inlet gas velocity distribution.

NPRNT - Indicator whose value must be that which designates the print unit for a given machine.

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%).

CZMDL - Fitted mass median diameter of the outlet particle size distribution under no-rap + rap conditions (μm).

CSIGMO - Fitted geometric standard deviation of the outlet particle size distribution under no-rap + rap conditions.

NRUN - Indicator that specifies which set of nonideal conditions is under consideration.

SNUCK - Particular value of ASNUCK(M).

ZIGGY - Particular value of AZIGGY(M).

RMMD - Particular value of ARD50(L) [μm].

RSIGMA - Particular value of ARSIGM(L).

D50 - Same as ZMMDI (μm).

SIGMAP - Same as SIGMI.

Of the above variables, the values of the following must be provided by the main program: DIAM, ONO, DXS, XMV, PCNT, CCF, LSECT, LINCS, PS, VG, ATOTAL, DD, ETAO, DL, PL, RHO, NS, ZMMDI, SIGMI, NONID, NRAPD, TDK, NUMSEC, NEFF, NTEMP, GFIT, VOS, TCS, ENDPT, NENDPT, ARD50, ARSIGM, ASNUCK, AZNUMS, AZIGGY, NPRNT, D50, and SIGMAP. The values of the following variables are determined in the subroutine: SCOREF, CZMDL, CSIGMO, NRUN, SNUCK, ZIGGY, RMMD, and RSIGMA. The values of these variables must be supplied to subroutine PRTSUM. In the above arrays, I, J, K, L, and M can not exceed values of 20, 10, 21, 10, and 15, respectively. The restrictions on I, J, K, L, and M limit the number of particle size bands, the number of electrical sections, the number of particle diameters in the inlet particle size distribution, the number of rapping puff particle size distributions, and the number of sets of nonideal conditions of σ_g and S, respectively.

Subroutine WADJST

This subroutine adjusts the no-rap migration velocities by applying the empirical correction factors given in Figure 7. These correction factors and their corresponding particle sizes are tabulated for 24 particle diameters between 0.2 μm and 4.5 μm in data statements. Table 1 shows the particle sizes and correction factors which are tabulated. Correction factors for no-rap migration velocities for particle diameters in the range 0.2 μm - 4.5 μm are found by interpolating the table. No-rap

TABLE 1. PARTICLE SIZES AND CORRECTION FACTORS FOR NO-RAP MIGRATION VELOCITIES TABULATED IN SUBROUTINE WADJST

Particle Diameter (μm)	Correction Factor	Particle Diameter (μm)	Correction Factor
0.20	2.430	0.80	1.790
0.25	2.325	0.85	1.760
0.30	2.240	0.90	1.740
0.35	2.170	0.95	1.710
0.40	2.110	1.00	1.685
0.45	2.050	1.50	1.500
0.50	2.000	2.00	1.370
0.55	1.965	2.50	1.270
0.60	1.920	3.00	1.180
0.65	1.885	3.50	1.115
0.70	1.850	4.00	1.050
0.75	1.820	4.50	1.000

migration velocities outside this range are left unchanged. Based on the adjusted no-rap migration velocities, the subroutine calculates for each particle size an adjusted no-rap collection fraction and the number of particles removed.

Figure 22 shows a detailed flow chart for this subroutine. This subroutine is called by subroutine ADJUST and all information which is transmitted between these subprograms is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

DIAM(I) - Midpoint of a given particle size band (m).

I - Index which specifies the different particle diameters.

WY - Enters the subroutine as a no-rap migration velocity and returns as an adjusted no-rap migration velocity (cm/sec).

ONO(I) - Number of particles per unit volume of gas for a given particle size band entering the precipitator (#/m^3).

PXS(I) - Number of particles per unit volume of gas for a given particle size band which are removed from the gas stream under adjusted no-rap conditions (#/m^3).

ATOTAL - Total collection plate area (m^2).

VG - Gas volume flow rate (m^3/sec).

EFESR - Enters the subroutine as a no-rap collection fraction and returns as an adjusted no-rap collection fraction.

All of the above variables must be supplied by subroutine ADJUST. The values of WY and EFESR are replaced by new values for particle sizes in the range 0.2 - 4.5 μm. In all of the uses above, I can not exceed a value of 20. The restriction on the value of I limits the number of particle size bands.

Subroutine LNDIST

This subroutine constructs a particle size distribution histogram for a specified log-normal distribution. For specified particle diameters, the fraction in each particle size band and cumulative fraction less than each particle size are determined. In order to use this subroutine, subroutine QTFE must be supplied.

The log-normal distribution function [$f_{L-N}(z)$] is given by the expression

$$f_{L-N}(z) = \frac{1}{\sigma_z \sqrt{2\pi}} \quad \mathrm{EXP} \left[- \frac{(z-\bar{z})^2}{2\sigma_z^{\,2}} \right] \quad , \qquad (58)$$

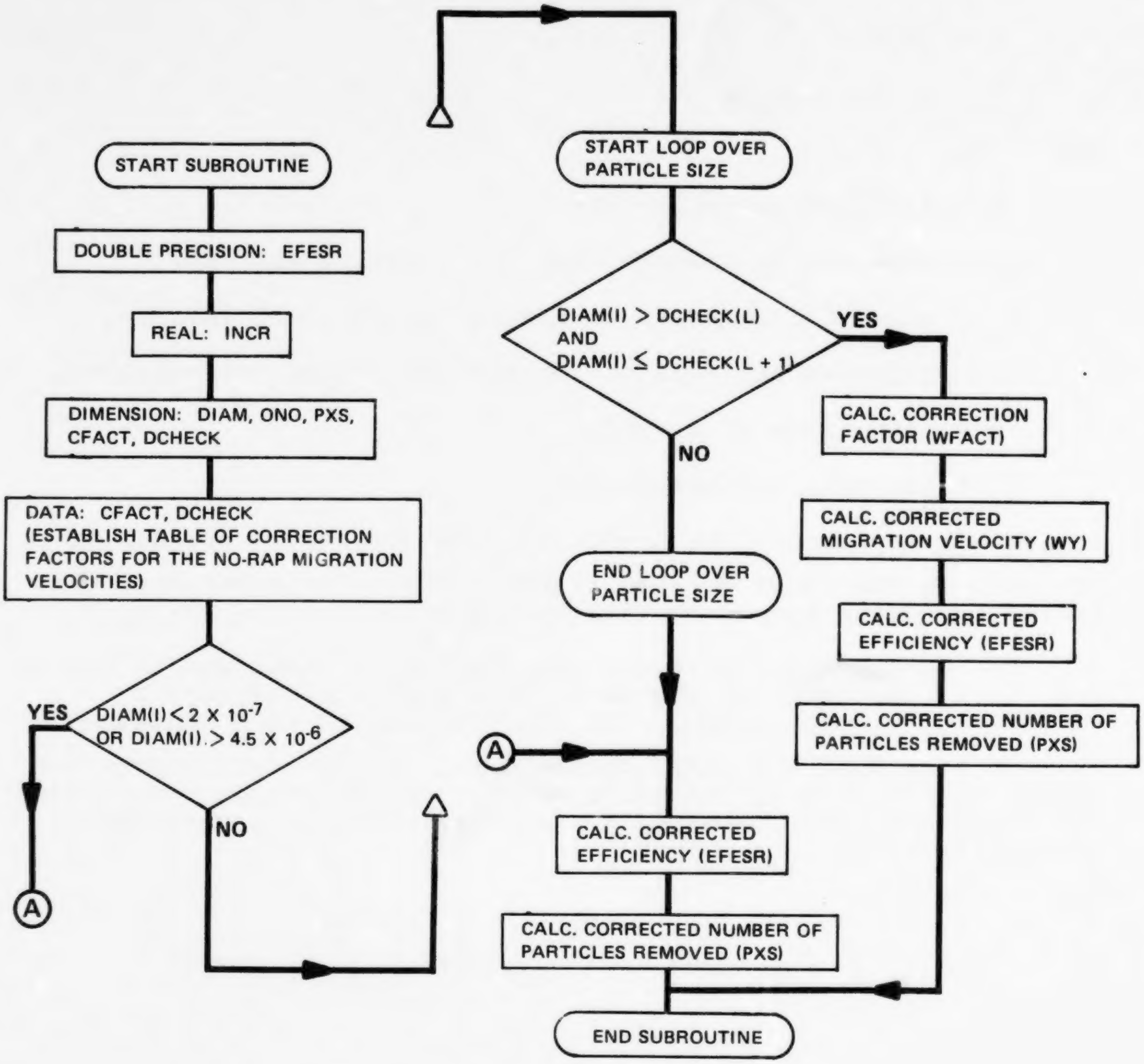

START SUBROUTINE
DOUBLE PRECISION: EFESR
REAL: INCR
DIMENSION: DIAM, ONO, PXS, CFACT, DCHECK
DATA: CFACT, DCHECK (ESTABLISH TABLE OF CORRECTION FACTORS FOR THE NO-RAP MIGRATION VELOCITIES)
DIAM(I) < 2 X 10-7 OR DIAM(I) > 4.5 X 10-6
YES
NO
A
START LOOP OVER PARTICLE SIZE
DIAM(I) > DCHECK(L) AND DIAM(I) ≤ DCHECK(L + 1)
YES
NO
CALC. CORRECTION FACTOR (WFACT)
CALC. CORRECTED MIGRATION VELOCITY (WY)
CALC. CORRECTED EFFICIENCY (EFESR)
CALC. CORRECTED NUMBER OF PARTICLES REMOVED (PXS)
END LOOP OVER PARTICLE SIZE
A
CALC. CORRECTED EFFICIENCY (EFESR)
CALC. CORRECTED NUMBER OF PARTICLES REMOVED (PXS)
END SUBROUTINE

Figure 22. Flow chart for subroutine WADJST.

where

$$\sigma_z = \ln \sigma_p \quad , \tag{59}$$

$$z = \ln d \quad , \tag{60}$$

$$\overline{z} = \ln d_{50} \quad , \tag{61}$$

and

d = particle diameter (μm),

d_{50} = mass median diameter for the distribution (μm),

σ_p = geometric standard deviation for the distribution,

z = independent variable for the log-normal distribution,

$\overline{z}$ = mean value of z, and

σ_z = standard deviation of z.

$f_{L-N}(z)\,dz$ represents the amount of mass (or other variable if desired) in the range between z and $z + dz$. The distribution is completely described by specifying the values of d_{50} and σ_p.

The subroutine constructs the log-normal distribution histogram by (1) determining the total mass contained between $z_1 = \ln 0.01$ and $z_n = \ln 1000.0$, (2) calculating the mass contained in each size band specified by the user, and (3) calculating the ratios of the mass contained in each size band to the total mass. The total mass (M) contained in the distribution is obtained in cumulative steps in the form

$$M = \int_{z_1}^{z_2} f_{L-N}(z)dz + \int_{z_2}^{z_3} f_{L-N}(z)dz + \int_{z_3}^{z_4} f_{L-N}(z)dz$$

$$+\cdots\cdots+ \int_{z_{n-2}}^{z_{n-1}} f_{L-N}(z)dz + \int_{z_{n-1}}^{z_n} f_{L-N}(z)dz \quad . \tag{62}$$

The integrals in equation (62) are evaluated numerically by calling subroutine QTFE which utilizes the Trapezoidal Rule. Each integration is performed by dividing the size band into 99 intervals and evaluating the integrand at 100 points. The value of each integral is stored as well as the cumulative sum. The user specifies the particle diameters in μm which correspond to the values of z from z_2 to z_{n-1} where $z_2 > -4.605$ and $z_{n-1} < 6.908$ ($d_2 > 0.01$ and $d_{n-1} < 1000.0$).

The mass fractions (F_i) for the size bands in equation (62) are obtained from the expressions

$$F_1 = \left(\int_{z_1}^{z_2} f_{L-N}(z)dz \right) /M$$

$$F_2 = \left(\int_{z_2}^{z_3} f_{L-N}(z)dz \right) /M$$

$$\begin{matrix} \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \end{matrix}$$

$$F_{n-1} = \left(\int_{z_{n-1}}^{z_n} f_{L-N}(z)dz \right) /M \quad , \qquad (63)$$

where there are n-1 size bands. Since the size bands specified by the user are contained in the range from z_2 to z_{n-1}, the excess mass fractions in the size bands z_1 to z_2 and z_{n-1} to z_n are added to the mass fraction in the size band z_{n-2} to z_{n-1} for the histogram which is returned from the subroutine. This is done to ensure that the size distribution used in the model accounts for 100% of the mass.

The cumulative mass fractions (S_i) for the specified diameters and size bands are obtained from

$$S_2 = F_1$$

$$S_3 = \sum_{i=1}^{2} F_i$$

$$S_4 = \sum_{i=1}^{3} F_i$$

$$\begin{matrix} \vdots & \vdots \end{matrix}$$

$$S_{n-1} = \sum_{i=1}^{n-1} F_i + \left(1 - \sum_{i=1}^{n-1} F_i \right) \quad , \qquad (64)$$

where the cumulative mass fraction less than the largest specified diameter is constrained to be a value of 1 by adjusting the mass fraction in the size band from z_{n-2} to z_{n-1}.

Figure 23 shows a detailed flowchart for this subroutine. This subroutine is called by the main program and subroutine ADJUST. Information which is transmitted to and from this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

D50 - Specified mass median diameter for a log-normal distribution (μm),

SIGMAP - Specified geometric standard deviation for a log-normal distribution,

PRCU(I) - Cumulative mass fractions for the log-normal distribution, and

PCNT(J) - Mass fraction in a given size band of the log-normal distribution.

The following is a list of the necessary variables which are in common with the main program and subroutine ADJUST.

NS - Number of specified particle size bands in the histogram for the log-normal distribution,

ENDPT(I) - Specified endpoints of the particle size band intervals in the histogram for the log-normal distribution (μm), and

NENDPT - Specified number of endpoints in the histogram for the log-normal distribution.

Of the above variables, the values of the following must be provided by the calling program or subprogram: D50, SIGMAP, NS, ENDPT, and NENDPT. PRCU and PCNT are determined in the subroutine. I and J can not exceed values of 21 and 20, respectively. The

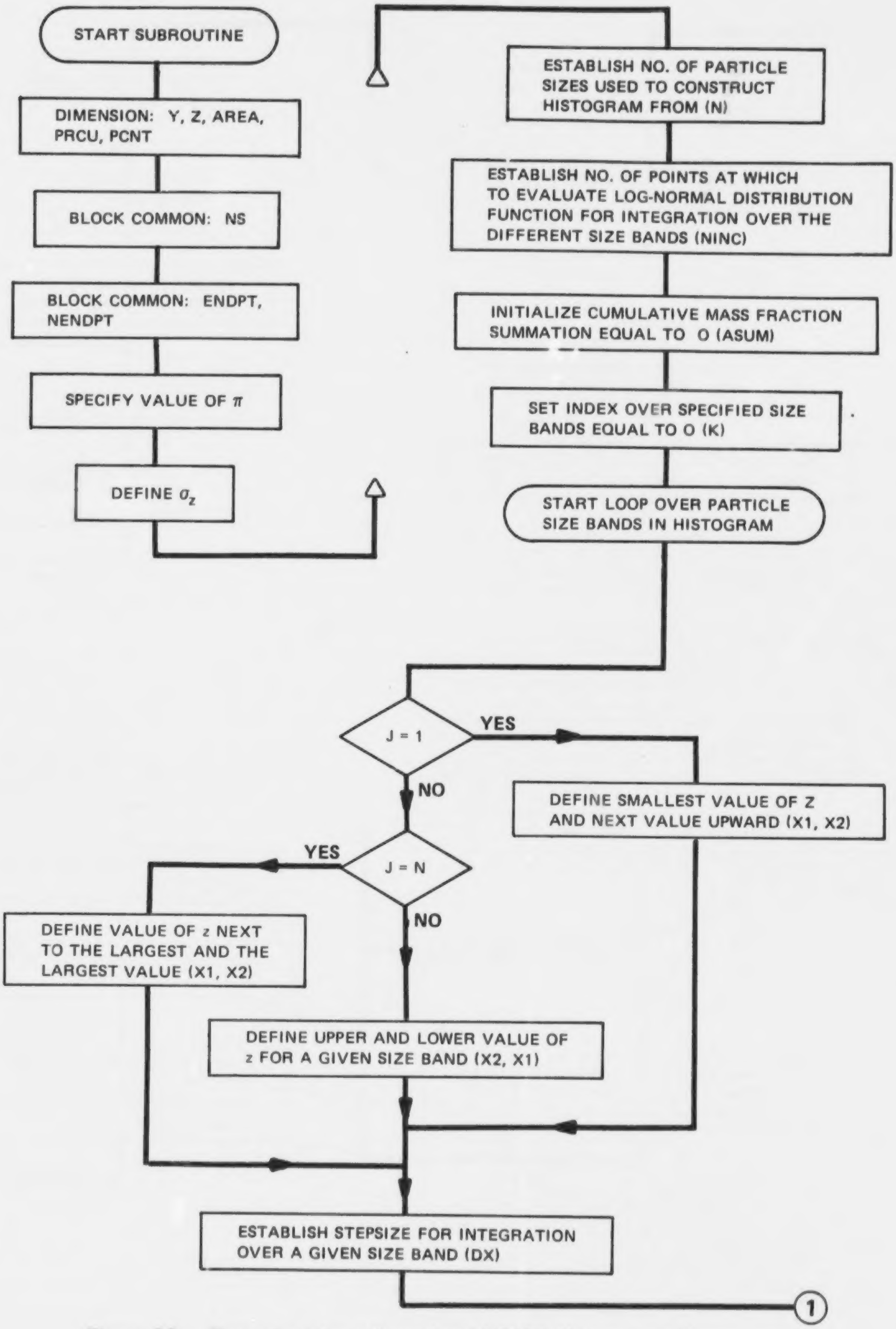

START SUBROUTINE
DIMENSION: Y, Z, AREA, PRCU, PCNT
BLOCK COMMON: NS
BLOCK COMMON: ENDPT, NENDPT
SPECIFY VALUE OF π
DEFINE σ_z
ESTABLISH NO. OF PARTICLE SIZES USED TO CONSTRUCT HISTOGRAM FROM (N)
ESTABLISH NO. OF POINTS AT WHICH TO EVALUATE LOG-NORMAL DISTRIBUTION FUNCTION FOR INTEGRATION OVER THE DIFFERENT SIZE BANDS (NINC)
INITIALIZE CUMULATIVE MASS FRACTION SUMMATION EQUAL TO O (ASUM)
SET INDEX OVER SPECIFIED SIZE BANDS EQUAL TO O (K)
START LOOP OVER PARTICLE SIZE BANDS IN HISTOGRAM
J = 1
YES
NO
DEFINE SMALLEST VALUE OF Z AND NEXT VALUE UPWARD (X1, X2)
J = N
YES
NO
DEFINE VALUE OF z NEXT TO THE LARGEST AND THE LARGEST VALUE (X1, X2)
DEFINE UPPER AND LOWER VALUE OF z FOR A GIVEN SIZE BAND (X2, X1)
ESTABLISH STEPSIZE FOR INTEGRATION OVER A GIVEN SIZE BAND (DX)
①

Figure 23. Flow chart for subroutine LNDIST (Sheet 1 of 3).

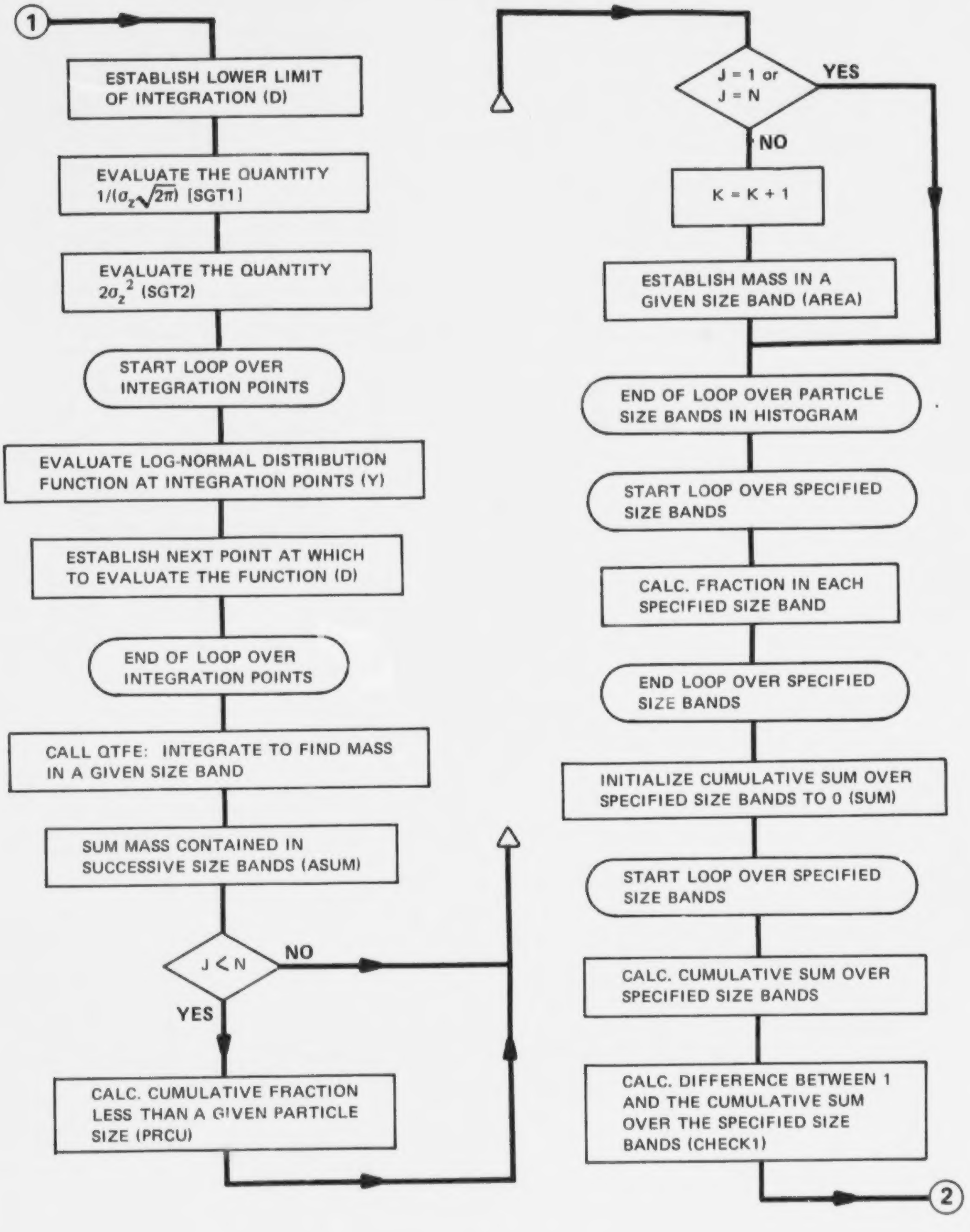

①
ESTABLISH LOWER LIMIT OF INTEGRATION (D)
EVALUATE THE QUANTITY $1/(\sigma_z\sqrt{2\pi})$ [SGT1]
EVALUATE THE QUANTITY $2\sigma_z^2$ (SGT2)
START LOOP OVER INTEGRATION POINTS
EVALUATE LOG-NORMAL DISTRIBUTION FUNCTION AT INTEGRATION POINTS (Y)
ESTABLISH NEXT POINT AT WHICH TO EVALUATE THE FUNCTION (D)
END OF LOOP OVER INTEGRATION POINTS
CALL QTFE: INTEGRATE TO FIND MASS IN A GIVEN SIZE BAND
SUM MASS CONTAINED IN SUCCESSIVE SIZE BANDS (ASUM)
$J < N$
NO
YES
CALC. CUMULATIVE FRACTION LESS THAN A GIVEN PARTICLE SIZE (PRCU)
$J = 1$ or $J = N$
YES
NO
$K = K + 1$
ESTABLISH MASS IN A GIVEN SIZE BAND (AREA)
END OF LOOP OVER PARTICLE SIZE BANDS IN HISTOGRAM
START LOOP OVER SPECIFIED SIZE BANDS
CALC. FRACTION IN EACH SPECIFIED SIZE BAND
END LOOP OVER SPECIFIED SIZE BANDS
INITIALIZE CUMULATIVE SUM OVER SPECIFIED SIZE BANDS TO 0 (SUM)
START LOOP OVER SPECIFIED SIZE BANDS
CALC. CUMULATIVE SUM OVER SPECIFIED SIZE BANDS
CALC. DIFFERENCE BETWEEN 1 AND THE CUMULATIVE SUM OVER THE SPECIFIED SIZE BANDS (CHECK1)
②

Figure 23. Flow chart for subroutine LNDIST (Sheet 2 of 3).

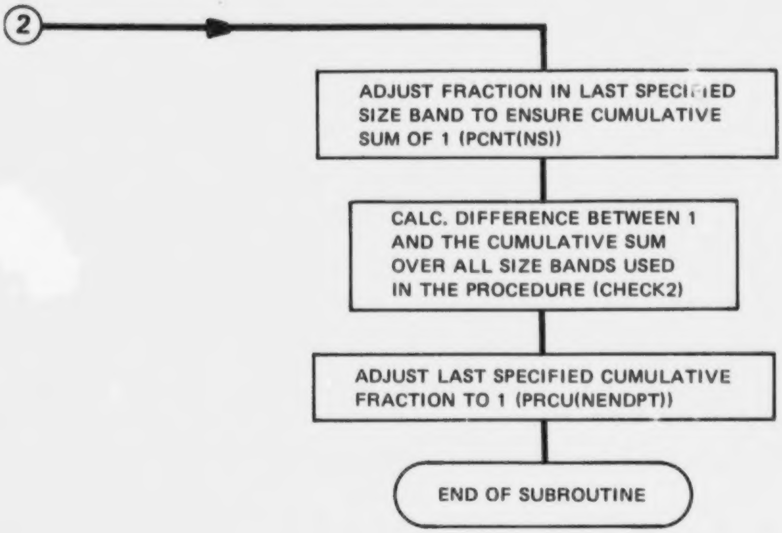

2
ADJUST FRACTION IN LAST SPECIFIED SIZE BAND TO ENSURE CUMULATIVE SUM OF 1 (PCNT(NS))
CALC. DIFFERENCE BETWEEN 1 AND THE CUMULATIVE SUM OVER ALL SIZE BANDS USED IN THE PROCEDURE (CHECK2)
ADJUST LAST SPECIFIED CUMULATIVE FRACTION TO 1 (PRCU(NENDPT))
END OF SUBROUTINE

Figure 23. Flow chart for subroutine LNDIST (Sheet 3 of 3).

restrictions on I and J limit the number of particle diameters in the inlet particle size distribution and the number of particle size bands, respectively.

Subroutine QTFE

This subroutine performs the integration of an equidistantly tabulated function by the trapezoidal rule.[37] Cumulative integral values (Z_i) are determined by

$$Z_i = Z_i(x) = \int_a^{x_i} y(x)dx \quad , \qquad (65)$$

where $x_i = a + (i-1)h$ and $i=1,2,\cdots,n$. The function values y_i are tabulated at the equidistant points x_i, where h is the increment size for the integration. Starting with the integral value $Z_1 = 0$, successive integral values Z_i $(i=2,3,\cdots,n)$ are computed by using the trapezoidal rule in the form

$$Z_i = Z_{i-1} + \frac{h}{2}(y_i + y_{i-1}) \quad . \qquad (66)$$

In applying the trapezoidal rule, it is assumed that the function to be integrated is continuous and can be differentiated at least twice.

This subroutine is called by subroutine LNDIST. Figure 24 shows a detailed flow chart for this subroutine. All information which is transmitted between subroutine LNDIST and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

DX - Increment size for the integration.

Y(I) - Table of function values at the equidistant points used in the integration procedure.

Z(I) - Cumulative integral values.

NINC - Number of points at which the function to be integrated is evaluated.

Of the above variables, the values of DX, Y, and NINC must be provided by the calling program (subroutine LNDIST). The values of Z are returned from subroutine QTFE.

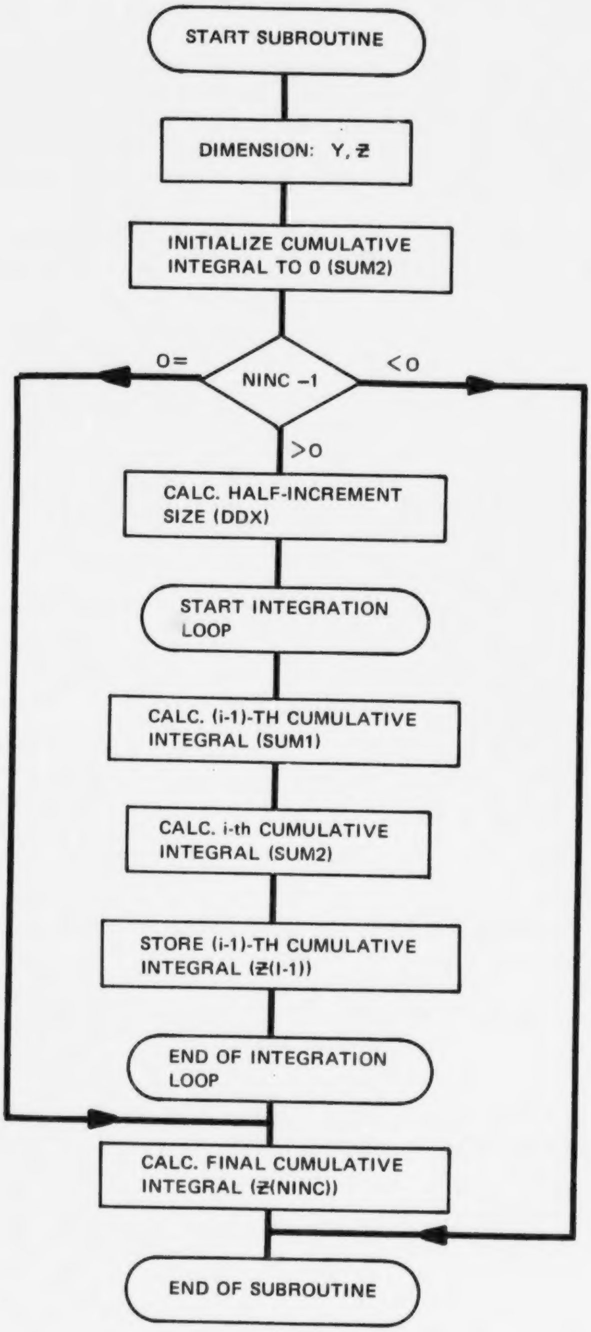

START SUBROUTINE
DIMENSION: Y, Ƶ
INITIALIZE CUMULATIVE INTEGRAL TO 0 (SUM2)
0=
NINC −1
<0
>0
CALC. HALF-INCREMENT SIZE (DDX)
START INTEGRATION LOOP
CALC. (i-1)-TH CUMULATIVE INTEGRAL (SUM1)
CALC. i-th CUMULATIVE INTEGRAL (SUM2)
STORE (i-1)-TH CUMULATIVE INTEGRAL (Ƶ(I-1))
END OF INTEGRATION LOOP
CALC. FINAL CUMULATIVE INTEGRAL (Ƶ(NINC))
END OF SUBROUTINE

Figure 24. Flow chart for subroutine QTFE.

Subroutine LNFIT

This subroutine fits a measured or calculated particle size distribution to a log-normal distribution. A mass median diameter, geometric standard deviation, and fit parameter are determined in order to describe the fitted log-normal distribution. In order to use this subroutine, subroutine CFIT must be supplied.

Using equation (58), we can write the cumulative fraction (S(X)) up to a given particle size for a log-normal distribution in the form

$$S(X) = \int_{-\infty}^{X} f_{L-N} \, dz$$

$$= \frac{1}{\sigma_z \sqrt{2\pi}} \int_{-\infty}^{X} \mathrm{EXP} \left[- \frac{(z-\bar{z})^2}{2\sigma_z^{\,2}} \right] dz \qquad (67)$$

where the symbols are as previously defined. By making a change in variable of the form

$$t = \frac{z-\bar{z}}{\sigma_z} \qquad (68)$$

and

$$dz = \sigma_z \, dt \quad , \qquad (69)$$

we can write equation (67) in the form

$$S(t') = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t'} \mathrm{EXP} \left[- \frac{t^2}{2} \right] dt \quad . \qquad (70)$$

The cumulative fraction (Q(t')) greater than a given particle size can be expressed in the form

$$Q(t') = \frac{1}{\sqrt{2\pi}} \int_{t'(Q)}^{\infty} \mathrm{EXP} \left[- \frac{t^2}{2} \right] dt \quad . \qquad (71)$$

S(t') and Q(t') are called inverse Gaussian (Normal) integrals.

The variable t'(Q) can be approximated by the expression[38]

$$t'(Q) = \phi - \left\{ \frac{a_0 + a_1 \phi + a_2 \phi^2}{1 + b_1 \phi + b_2 \phi_2 + b_3 \phi^3} \right\} \quad , \qquad (72)$$

where the error in $t'(Q)$ is equal to or less than 0.00045 and $a_0 = 2.515517$, $a_1 = 0.802853$, $a_2 = 0.010328$, $b_1 = 1.432788$, $b_2 = 0.189269$, and $b_3 = 0.001308$. The approximate expression for $t'(Q)$ is valid for $0<Q(t') \leq 0.5$. The variable ϕ is defined as

$$\phi = \sqrt{\ln \left(\frac{1}{Q^2}\right)} \quad . \qquad (73)$$

Since $S(t') + Q(t') = 1$, equation (72) can be used for $t'(S)$ where $0.5 \leq S(t')<1$. In this case,

$$\phi = \sqrt{\ln \left(\frac{1}{1-Q}\right)^2} = \sqrt{\ln \left(\frac{1}{S}\right)^2} \quad . \qquad (74)$$

Due to the symmetry of the Gaussian (Normal) distribution function, $S(-\infty) = 0$, $S(0) = 0.5$, and $S(\infty) = 1.0$. In addition, we may employ the relationship

$$t'(Q = u) = - t'(Q = 1-u) \quad , \qquad (75)$$

where $0 \leq u \leq 1$.

The variable $t'(S)$ which is related to a true log-normal distribution can be determined from equations (72), (74), and (75) for any given cumulative fraction S. Inspection of equations (67), (68), and (70) shows that the variable t' corresponds to the natural logarithm of a quantity which is linearly related to the natural logarithm of a given particle size. In the procedure used to fit the actual cumulative distribution to a log-normal distribution, the value of t' and the natural logarithm of the actual particle size (z') are determined for each actual cumulative fraction S. The set of points (z',t') constitute a function that can be plotted on log-log axes. If the actual distribution is a log-normal distribution,

$$t' = \frac{z'}{\sigma_z} - \frac{\overline{z}'}{\sigma_z} \qquad (76)$$

for all z' and t' and the points (z',t') will lie on a straight line which has a slope of $\frac{1}{\sigma_z}$ and a t'-intercept of $-\frac{\overline{z}'}{\sigma_z}$. The points (z',t') are fitted to a straight line of the form

$$t' = A + Bz' \qquad (77)$$

by calling subroutine CFIT which uses a linear least squares fit procedure.

Since $t' = 0$ at the point where 50% of the distribution has been accumulated, the fitted, actual d_{50} can be obtained from

$$0 = A + Bz' = A + B \ln d_{50} \quad . \qquad (78)$$

Thus,

$$d_{50} = \mathrm{EXP}\ (-\ A/B) \quad . \qquad (79)$$

In order to obtain the geometric standard deviation (σ_p) of the fitted log-normal distribution, it is recognized from equations (76), (77), and (79) that

$$A = -\frac{\bar{z}}{\sigma_z} = -\frac{\ln d_{50}}{\sigma_z} = \frac{A}{B \ln \sigma_p} \qquad (80)$$

or

$$\sigma_p = \mathrm{EXP}\ (1/B) \quad . \qquad (81)$$

Figure 25 shows a detailed flow chart for this subroutine. This subroutine is called by the main program and subroutine ADJUST. Information which is transmitted to and from this subroutine is transferred through calling arguments and block common statements. The following is a sequential list of the calling arguments and their descriptions.

PRCU(I) - Measured or known cumulative mass fractions.

D50 - Mass median diameter obtained from the fit of the actual distribution to a log-normal distribution (μm).

SIGMAP - Geometric standard deviation obtained from the fit of the actual distribution to a log-normal distribution.

GFIT - Goodness of fit parameter for the log-normal fit.

The following is a list of the necessary variables which are in common with the main program and subroutine ADJUST.

ENDPT(I) - Particle diameters corresponding to the measured or known cumulative mass fractions (μm).

NENDPT - Number of points in the measured or known distribution.

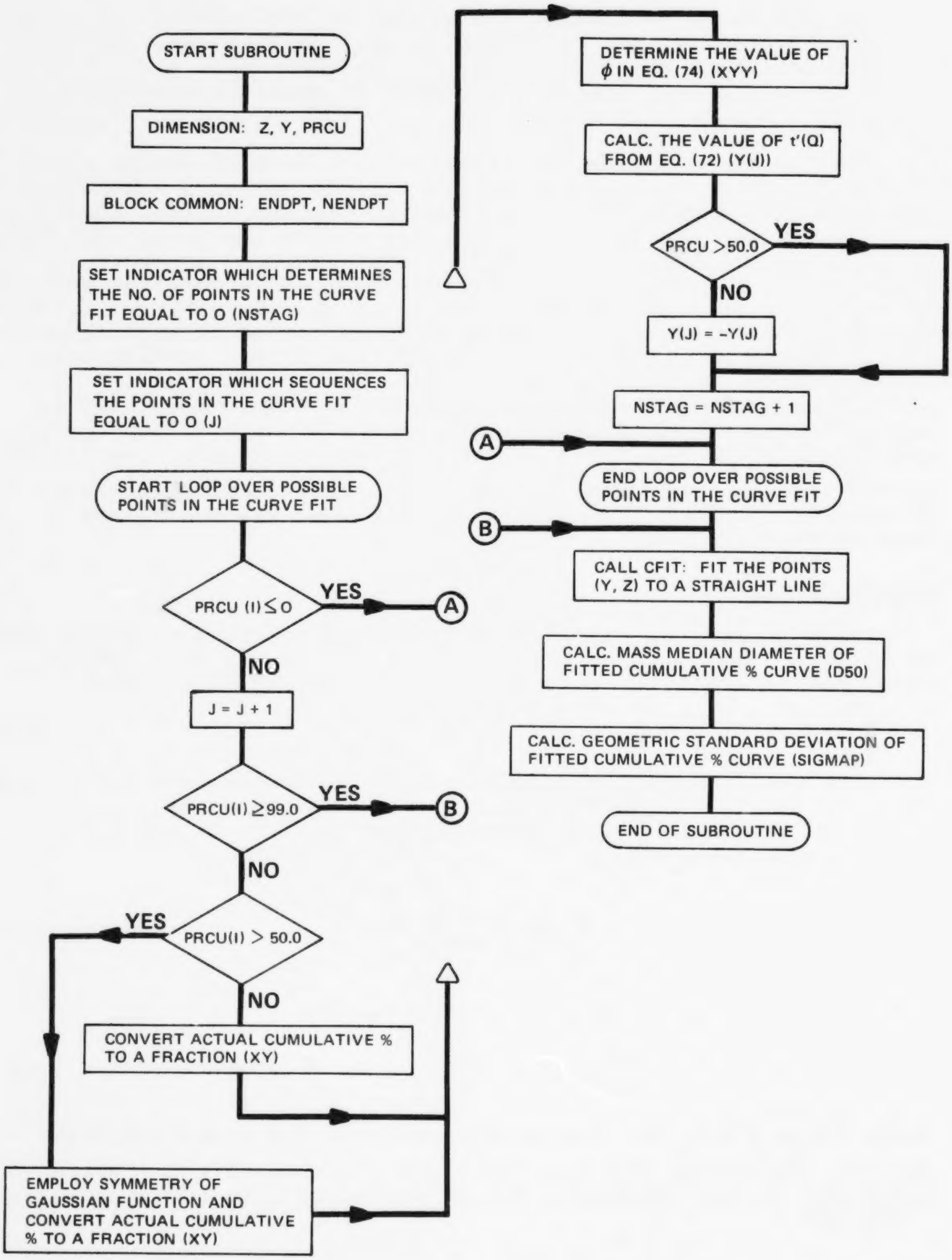

START SUBROUTINE
DIMENSION: Z, Y, PRCU
BLOCK COMMON: ENDPT, NENDPT
SET INDICATOR WHICH DETERMINES THE NO. OF POINTS IN THE CURVE FIT EQUAL TO O (NSTAG)
SET INDICATOR WHICH SEQUENCES THE POINTS IN THE CURVE FIT EQUAL TO O (J)
START LOOP OVER POSSIBLE POINTS IN THE CURVE FIT
PRCU (I) ≤ O
YES
A
NO
J = J + 1
PRCU(I) ≥ 99.0
YES
B
NO
PRCU(I) > 50.0
YES
NO
CONVERT ACTUAL CUMULATIVE % TO A FRACTION (XY)
EMPLOY SYMMETRY OF GAUSSIAN FUNCTION AND CONVERT ACTUAL CUMULATIVE % TO A FRACTION (XY)
DETERMINE THE VALUE OF ϕ IN EQ. (74) (XYY)
CALC. THE VALUE OF t'(Q) FROM EQ. (72) (Y(J))
PRCU > 50.0
YES
NO
Y(J) = -Y(J)
NSTAG = NSTAG + 1
A
END LOOP OVER POSSIBLE POINTS IN THE CURVE FIT
B
CALL CFIT: FIT THE POINTS (Y, Z) TO A STRAIGHT LINE
CALC. MASS MEDIAN DIAMETER OF FITTED CUMULATIVE % CURVE (D50)
CALC. GEOMETRIC STANDARD DEVIATION OF FITTED CUMULATIVE % CURVE (SIGMAP)
END OF SUBROUTINE

Figure 25. Flow chart for subroutine LNFIT.

Of the above variables, the values of PRCU, ENDPT, and NENDPT must be supplied by the calling program. D50, SIGMAP, and GFIT are determined in the subroutine. I can not exceed a value of 21. The restriction on I limits the number of particle diameters in the particle size distribution.

In the calculations, all points which have an actual cumulative fraction of zero are ignored. Since measured cumulative particle size distributions may tend to flatten out for the larger particle sizes, the calculation is cut off at the point where 99% of the distribution is accumulated. This is done in order to keep the curve fit from being prejudiced towards the flat portion of the curve even though the majority of the distribution is log-normal. The cumulative fractions and corresponding particle diameters should be stored in arrays PRCU and ENDPT, respectively, in order from smallest to largest values. If the goodness of fit parameter GFIT, which is determined in subroutine CFIT, is nearly 1, the actual distribution is very close to a log-normal distribution and the fitted d_{50} and σ_p are meaningful quantities. If GFIT is much less than 1, the actual distribution should be examined in order to determine if the fitted d_{50} and σ_p are meaningful quantities.

Subroutine CFIT

This subroutine fits a set of data points to a straight line by using a least squares fit procedure.[39] If the data points (x,y) are to be fitted to a linear relationship of the form

$$y = a + bx \quad , \tag{82}$$

the problem is to find the undetermined coefficients a and b such that the line is a good fit to the data. In this case, application of the principle of least squares results in two normal equations of the form

$$ma + \sum x_j b = \sum y_j \tag{83}$$

and

$$\sum x_j \, a + \sum x_j^2 \, b = \sum x_j y_j \quad , \tag{84}$$

where (x_j, y_j) are the data points and m is the number of data points. Equations (83) and (84) form a system of two simultaneous equations in two unknowns. The solutions of this system of equations are

$$a = \frac{1}{\Delta}\left[\left(\sum y_j\right)\left(\sum x_j^2\right) - \left(\sum x_j y_j\right)\left(\sum x_j\right)\right] \tag{85}$$

and

$$b = \frac{1}{\Delta}\left[m\left(\sum x_j y_j\right) - \left(\sum y_j\right)\left(\sum x_j\right)\right] , \tag{86}$$

where

$$\Delta = m\left(\sum x_j^2\right) - \left(\sum x_j\right)^2 \quad . \tag{87}$$

With the above determination of a and b, the least squares fit to the data is obtained.

A linear-correlation coefficient r can be constructed in order to measure the degree of linear correlation or the probability that a linear relationship exists between the two observed variables x and y. Since we are interested in the interrelationship between the variables x and y, we can equally well consider x as a function of y and ask if the data correspond to a straight line of the form

$$x = a' + b' y \quad . \tag{88}$$

The values of the coefficients a′ and b′ will be different from those of a and b in equation (82), but they are related if the variables x and y are correlated.

The inverse slope b′ is determined in the same manner as b

$$b' = \frac{1}{\Delta'}\left[m\left(\sum x_j y_j\right) - \left(\sum y_j\right)\left(\sum x_j\right)\right] \tag{89}$$

where

$$\Delta' = m\left(\sum y_j^2\right) - \left(\sum y_j\right)^2 \quad . \tag{90}$$

If there is no correlation between the variables x and y, the least-squares fit must yield a horizontal straight line and b = b′ = 0.

If there is complete correlation between x and y, there exists a relationship between the coefficients a and b of equation (82) and the coefficients a′ and b′ of equation (88). From equations (82) and (88),

$$y = -\frac{a'}{b'} + \frac{1}{b'}x = a + bx \quad . \tag{91}$$

Equating coefficients gives

$$a = -\frac{a}{b} \tag{92}$$

and

$$b = \frac{1}{b'} \quad . \tag{93}$$

If there is complete correlation, we see that $bb' = 1$. If there is no correlation, both b and b' are 0. Thus, the quantity

$$r = \sqrt{bb'} \tag{94}$$

is defined as the linear-correlation coefficient and is used as a measure of the degree of linear correlation. The value of r ranges from 0, when there is no correlation, to 1, when there is complete correlation.

In the context of the model of electrostatic precipitation, r is called the goodness of fit parameter. If r is much less than 1, the coefficients a and b, which are also used in subroutine LNFIT, may not lead to meaningful information for the user.

This subroutine is called by subroutine LNFIT. Figure 26 shows a detailed flow chart for this subroutine. All information which is transmitted between subroutine LNFIT and this subroutine is transferred through calling arguments. The following is a sequential list of the calling arguments and their descriptions.

A - Constant term in the fitted linear relationship.

B - Coefficient of the independent variable in the fitted linear relationship.

R - Linear correlation coefficient (goodness of fit parameter).

NSTAG - Number of data points.

Z(I) - Measured or known values of the independent variable.

Y(I) - Measured or known values of the dependent variable.

Of the above variables, the values of NSTAG, Z, and Y must be provided by the calling program (subroutine LNFIT). The values

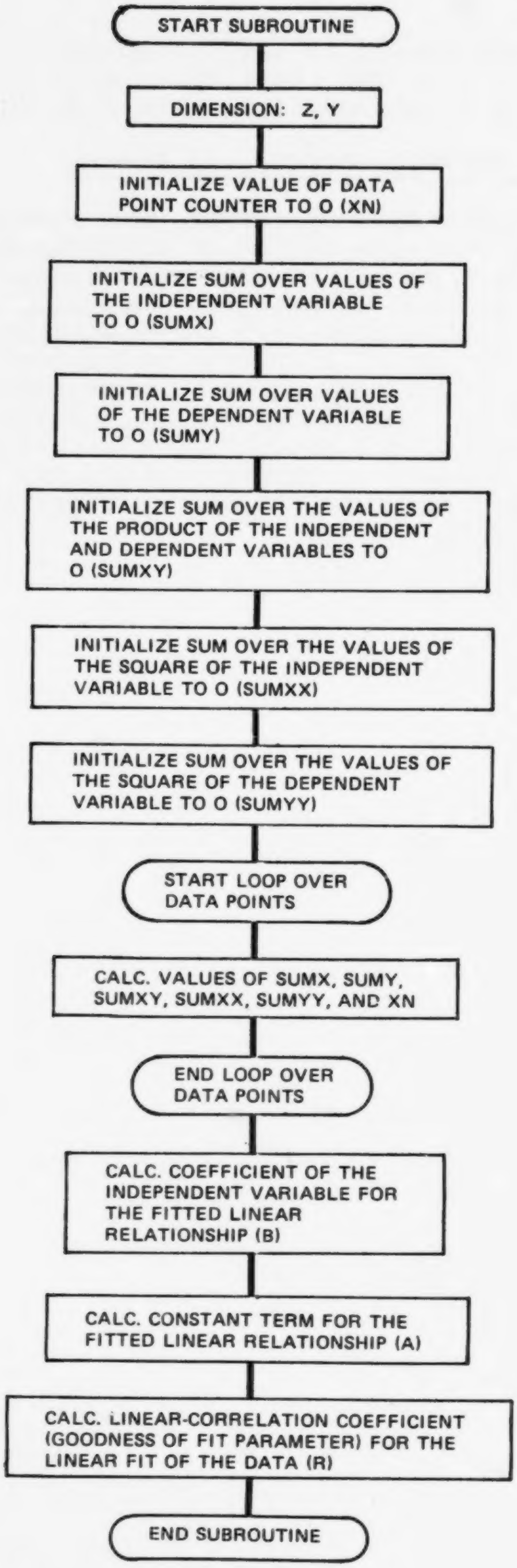

START SUBROUTINE
DIMENSION: Z, Y
INITIALIZE VALUE OF DATA POINT COUNTER TO O (XN)
INITIALIZE SUM OVER VALUES OF THE INDEPENDENT VARIABLE TO O (SUMX)
INITIALIZE SUM OVER VALUES OF THE DEPENDENT VARIABLE TO O (SUMY)
INITIALIZE SUM OVER THE VALUES OF THE PRODUCT OF THE INDEPENDENT AND DEPENDENT VARIABLES TO O (SUMXY)
INITIALIZE SUM OVER THE VALUES OF THE SQUARE OF THE INDEPENDENT VARIABLE TO O (SUMXX)
INITIALIZE SUM OVER THE VALUES OF THE SQUARE OF THE DEPENDENT VARIABLE TO O (SUMYY)
START LOOP OVER DATA POINTS
CALC. VALUES OF SUMX, SUMY, SUMXY, SUMXX, SUMYY, AND XN
END LOOP OVER DATA POINTS
CALC. COEFFICIENT OF THE INDEPENDENT VARIABLE FOR THE FITTED LINEAR RELATIONSHIP (B)
CALC. CONSTANT TERM FOR THE FITTED LINEAR RELATIONSHIP (A)
CALC. LINEAR-CORRELATION COEFFICIENT (GOODNESS OF FIT PARAMETER) FOR THE LINEAR FIT OF THE DATA (R)
END SUBROUTINE

Figure 26. Flow chart for subroutine CFIT.

of A, B, and R are calculated in the subroutine. The index I can not exceed a value of 21. The restriction on I limits the number of particle diameters in the particle size distribution.

Subroutines PRTINP, PRTINC, PRTCHG, and PRTSUM

Subroutines PRTINP, PRTINC, PRTCHG, and PRTSUM perform the function of printing out information of importance to the user. Since these subroutines do not involve operations based on physical principles or numerical techniques, they will not be discussed in detail. However, the output from these subroutines is discussed in detail in Volume 2. Briefly, PRTINP prints out all the input data to the program, PRTINC prints out the results of calculations which are a function of incremental length through the precipitator, PRTCHG prints out information concerning the charge on each particle size in each incremental length through the precipitator, and PRTSUM prints out a summary table of precipitator performance and operating parameters.

SECTION 8

DESCRIPTION OF INPUT DATA

GENERAL DESCRIPTION

The format of the original computer program which performs the calculations in the model for electrostatic precipitation has been re-structured to make the inputting of data less cumbersome. The number of cards which is necessary to input data has been reduced significantly by allowing different operating conditions to be analyzed from one basic set of input data. Due to the fact that several options are available in using the model, the number of cards and type of information in the input data may vary from one set of data to the next. Thus, it is necessary for the user to familiarize himself with the logic associated with the input data in order to ensure that the desired operations will be performed.

Some of the input variables are read into the program in British units whereas others are in MKS units. All input data which are in British units are converted to MKS units prior to performing the calculations. The input variables and format specifications are discussed in detail in the following subsection.

CONSTRUCTION OF THE BASIC DATA SET

The following is a sequential listing of the variables in the first group of data which is read in, along with the descriptions of the variables and the format specifications.

(1) NENDPT is the number of discrete points on a cumulative percent versus particle diameter curve. NENDPT is specified by the user and must have a value of at least 1 but not greater than 21. If NENDPT has a value of 99, the program terminates. If 21<NENDPT<99, the program will terminate abnormally during execution. NENDPT is read in with an I2 format and must be right justified in columns 1-2.

(2) NDATA is an indicator which tells the program to look for a certain type of data set. NDATA can have four possible values which will cause the program to look for the following data set types:

1 - A complete data set must be inputted. NDATA must have this value on the first data set.

2 - Only cards 1 and 2 and data concerning size distribution information must be inputted. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of particle size distribution on precipitator performance with all other variables held fixed.

3 - Only cards 1 and 2 and information concerning the gas volume flow and gas velocity must be inputted. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of specific collection area (SCA) on precipitator performance with all other variables held fixed.

4 - Only cards 1 and 2 and information concerning the applied voltage and current must be inputted. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of the electrical conditions on precipitator performance with all other variables held fixed.

NDATA is read in with an I2 format and must be right justified in columns 3-4. If NDATA $\neq$ 1,2,3, or 4, an error message will be given by the computer at the point in the program where NDATA is used in a "computed go to statement" (line 64). Depending on the particular computer, the program may or may not terminate at this point. If the program continues to execute, it may terminate abnormally at a later point in the program due to incorrect usage of the input data. If the program terminates normally, the calculations may or may not be correct, depending on the input data and the action taken by the computer.

The overall format for this group is (2I2). The data contained in this group is on the first card and this card must be the first card in each new data set.

Data group 2 is for specifying information which will identify the data set which is under consideration. All or part of columns 1-80 on data card 2 can be used in identifying the data set. The overall format for this card is (40A2). This data group must be the second card in each new data set.

At this point, the third and successive data groups depend on the choice of the value of NDATA. The basic data set must be read into the program before shortened data sets can be used. For NDATA=1, the program reads in the data groups in the basic data set in the sequence discussed below.

The following is a sequential listing of the variables in data group 3, along with the descriptions of the variables and the format specifications.

(1) NEST is an indicator which can have the values of 1 and 2. If NEST = 1, the program will perform extensive, detailed calculations in order to determine precipitator performance. If NEST = 2, estimation procedures are used to determine precipitator performance. Both of these options have been discussed in detail in Volume 1. Use of the estimation procedure will result in considerable savings in computer time and can be used to establish trends or to establish ranges over which to apply the more rigorous calculations. NEST is read in with an I2 format and must be right justified in columns 1-2.

(2) NDIST is an indicator which can have the values of 1 and 2. If NDIST = 1, the user must supply the inlet particle size distribution. If NDIST = 2, the program will construct a log-normal particle size distribution based on parameters provided by the user. The technique used to construct the log-normal size distribution is described in Volume 1. NDIST is read in with an I2 format and must be right justified in columns 3-4.

(3) NVI is an indicator which can have the values of 1 and 2. If NVI = 1, the user must supply known or measured values of the operating applied voltage and current. If NVI = 2, the program will construct a voltage-current curve (or curves) for a specified wire-plate geometry up to a voltage which is specified by the user. Both of the techniques for determining the electrical conditions are discussed in Volume 1. NVI is read in with an I2 format and must be right justified in columns 5-6.

(4) NX is the number of grid points in the x-direction (perpendicular to the gas flow) which is used in the numerical techniques that determine the electrical conditions. NX can not exceed a value of 15. If NVI = 1, sufficient accuracy can normally be obtained with NX ≥ 11. If NVI = 2, NX should be set equal to 15. NX is read in with an I2 format and must be right justified in columns 7-8.

(5) NY is the number of grid points in the y-direction (parallel to the gas flow) which is used in the numerical techniques that determine the electrical conditions. If NVI = 1, sufficient accuracy can normally be obtained with NY $\geq$ 9. If NVI = 2, NY should be set equal to 15. NY is read in with an I2 format and must be right justified in columns 9-10.

(6) NITER is an indicator which serves two different purposes. If NVI = 1, the value of NITER determines the maximum number of iterations the program will make on a loop which converges on overall mass collection efficiency. If the overall mass collection efficiency converges within 0.05% before NITER iterations, the calculation of collection efficiencies is completed at this point. NITER serves the purpose of cutting the calculation off in a reasonable amount of time when convergence requires more iterations and computer time than is warranted. For normal inlet mass loadings and particle size distributions a value of NITER = 2 is sufficient. For high inlet mass loadings or very fine particle size distributions a value of NITER = 3 or 4 may be necessary to provide sufficient accuracy. If NVI = 2, the value of NITER determines the number of iterations which will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions. In its present stage of development, the calculation procedure yields the same results for all values of NITER. Thus, in this case, set NITER = 1. The calculation procedure is discussed in Appendix A of Volume 1. NITER is read in with an I2 format and must be right justified in columns 11-12.

(7) NCALC is an indicator which can have the values of 0 and 1. If NCALC = 0, particle charge is determined by using equation (12) in Volume 1. Due to the number of times particle charge must be calculated and the use of numerical techniques in order to solve the charging equation, the particle charging calculations for NCALC = 0 take a considerable amount of computer time. If NCALC = 1, particle charge is estimated empirically by using the sum of the charges predicted from classical field and thermal charging theories [see equation (15) in Volume 1]. In this case, particle charge can be determined very rapidly from analytical expressions. Thus, in those cases where a significantly shorter run time is more important than the best accuracy possible, NCALC should be set equal to 1. If NEST = 2, particle charge will be performed as if NCALC = 1 regardless of the value of NCALC. NCALC is read in with an I2 format and must be right justified in columns 13-14.

(8) NRAPD is an indicator which specifies the number of rapping puff particle size distributions which will be utilized by the program in predicting the effect of rapping reentrainment on overall mass collection efficiency. NRAPD must have a value of at least 1 and can not exceed a value of 10. If NRAPD = 1, the program will determine the rapping puff particle size distribution based on the average of data obtained from several field tests on full-scale precipitators. These tests yield an average rapping puff particle size distribution with a mass median diameter (MMD) of 6.0 μm and a geometric standard deviation (σ_p) of 2.5. The technique which is used to predict rapping losses is discussed in Volume 1. If NRAPD is greater than one, the user must supply a MMD and σ_p of a log-normal distribution corresponding to each value of NRAPD greater than 1. The program will determine the rapping puff particle size distribution based on the specified combinations of MMD and σ_p. The case for NRAPD = 1 will always be performed. Each rapping puff particle size distribution is used in conjunction with the same basic ideal calculation and its effect is determined with very little expenditure of computer time. NRAPD is read in with an I2 format and must be right justified in columns 15-16.

(9) NEFF is an indicator which can have the values of 1 and 2. If NEFF = 1, the total mass reentrained at the outlet due to rapping is determined from the mass collected in the last field under adjusted no-rap conditions. If NEFF = 2, the total mass reentrained at the outlet due to rapping is determined from the mass which would be collected in the last field under unadjusted ideal conditions. NEFF should normally be taken to be 1 since this case is physically meaningful. A value of NEFF = 2 will result in rapping losses which are significantly greater than for NEFF = 1. Thus, a value of NEFF = 2 should only be used when a precipitator design which is conservative with respect to rapping losses is desired. NEFF is read in with an I2 format and must be right justified in columns 17-18.

(10) NTEMP is an indicator which can have the values of 1 and 2. The mass reentrained due to rapping will differ for cold-side and hot-side precipitators. If NTEMP = 1, the mass reentrained due to rapping is estimated based on an equation for cold-side precipitators. If NTEMP = 2, the mass reentrained due to rapping is estimated based on equation for hot-side precipitators. NTEMP is read in with an I2 format and must be right justified in columns 19-20.

(11) NONID is an indicator which specifies the number of combinations of normalized gas velocity standard deviation (σ_g) and gas bypassage fraction and/or particle reentrainment fraction without rapping (S) which are to be used to simulate the possible nonideal conditions. The procedures used to account for these nonideal effects are described in Volume 1. NONID must have a value of at least 1 and can not exceed a value of 15. Each set of nonideal conditions is used in conjunction with the same basic ideal calculation and its effect is determined with very little expenditure of computer time. NONID is read in with an I2 format and must be right justified in columns 21-22.

The overall format for this data group is (11I2) and all the data are contained on the third data card.

The next data group which is read in depends on the values of NCALC and NVI. If NCALC = 0, the rigorous charging theory is used. In this case, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) NN is the number of increments in the Runge-Kutta integration of equation (12) in Volume 1. If NVI = 1, a value of NN = 10 normally provides sufficient accuracy when the precipitator is divided into incremental lengths of approximately 0.305m or less. If NVI = 2, a value of NN = 5 normally provides sufficient accuracy. NN is read in with an I2 format and must be right justified in columns 1-2.

(2) NUMINC is the number of increments in the Simpson's Rule integration over θ in equation (12) in Volume 1. NUMINC must be an even number and a value of NUMINC = 20 normally provides sufficient accuracy. In order to speed up the calculations, NUMINC can be reduced to a value as low as 10 without causing too great a change in the results. The use of values of NUMINC which are less than 10 is not recommended. NUMINC is read in with an I2 format and must be right justified in columns 3-4.

The overall format for this data group is (2I2) and all the data are contained on a single card. If NCALC = 1, the above data group is not read into the program.

If NVI = 2, the model must calculate a voltage-current curve. In this case, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) IFINAL is an indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points. This indicator allows the user to have the V-I calculation terminated at a point before the specified operating voltage is reached whenever it is taking an excessive number of points to reach the specified operating voltage. IFINAL is read in with an I2 format and must be right justified in columns 1-2.

(2) JI1 is an indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve. Since the voltage-current calculation finds the applied voltage corresponding to a specified value of current density, this indicator allows the user to cover a large range of current densities without using an excessive number of points. JI1 is read in with an I2 format and must be right justified in columns 3-4.

(3) JI2 is an indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve. JI2 serves the same function as JI1 and JI2 must have a value greater than JI1 for proper usage. JI2 is read in with an I2 format and must be right justified in columns 5-6.

(4) VISKIP is an indicator which may have the values of 0 and 1. If VISKIP = 0, a voltage-current curve will be calculated up to a specified operating voltage for each successive length increment of the precipitator. If VISKIP = 1, only the operating current density which corresponds to a specified operating voltage will be calculated based on an estimation procedure discussed in Volume 1. In most cases, the user will want to set VISKIP = 1 since this will result in a prediction of the operating current density in each increment of length of the precipitator without using the large amounts of computer time required by the calculation of a voltage-current curve. Only extremely detailed analysis would warrant setting VISKIP = 0. VISKIP is read in with an I2 format and must be right justified in columns 7-8.

(5) VISAME is an indicator which may have the values of 1 and 2. The proper use of VISAME can result in significant savings in computer time whenever the applied voltage is the same in each electrical section. If the applied voltage is the same in each electrical section, set VISAME = 1 and only one "clean" voltage-current curve

will be calculated. If VISAME = 1, as many data sets as desired can be read into the program and all calculations will be based on the one "clean" voltage-current calculation. The use of VISAME = 1 is especially beneficial in studying hypothetical cases due to the large savings in computer time. If the applied voltage differs from one electrical section to the next, the user must set VISAME = 2. Whenever the operating voltage and current are unknown and the user must specify the use of the voltage-current calculations (NVI = 2), the quickest run time will occur when VISKIP = 1 and VISAME = 1. The longest run time will occur when VISKIP = 0 and VISAME = 2. VISAME is read in with an I2 format and must be right justified in columns 9-10.

The overall format for this data group is (5I2) and all data are contained on a single card. If NVI = 1, the above data group is not read into the program.

The following is a sequential listing of the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) DL is the inlet particulate mass loading in units of grains/ft^3. DL is read in with a F8.0 format and must be left justified in columns 1-8.

(2) PL is the total electrical length of the precipitator in units of feet. PL is read in with a F8.0 format and must be left justified in columns 9-16.

(3) ETA0 is the overall mass collection efficiency in units of percent and it has two different interpretations depending upon the value of NVI. If NVI = 1, ETA0 represents the measured or estimated overall mass collection efficiency and is used as a test for convergence in an iteration loop on overall mass collection efficiency. If NVI = 2, ETA0 simply represents the desired design efficiency and is not used in the calculations. ETA0 is read in with a F8.0 format and must be left justified in columns 17-24.

(4) DD is the density of the particles in units of kg/m^3. DD is read in with a F8.0 format and must be left justified in columns 25-32.

(5) EPS is the dielectric constant of the particles for use in the particle charging calculations and is dimensionless. Values of EPS must be equal to or greater than 1. In most industrial applications, the flue gas is sufficiently humidified so that the particle surface becomes conductive and a value of EPS = 100 can be used to simulate

a conductor. EPS is read in with a F8.0 format and must be left justified in columns 33-40.

(6) VRATIO is the ratio of the peak voltage to the average voltage and is dimensionless. In the calculation of particle charge, it is assumed that the particles will charge to an extent determined by the peak voltage rather than the average voltage. For industrial applications, VRATIO has a value around 1.2. VRATIO is read in with a F8.0 format and must be left justified in columns 41-48.

(7) US is the ionic mobility at standard temperature (273°K) and standard pressure (1 atm) and is in units of $m^2/(V\text{-sec})$. This mobility is referred to as the "reduced mobility". Values to use for reduced ionic mobilities for flue gas compositions are not well-established at the present time. The reduced ionic mobility for air is in the range $1.2\text{-}2.1 \times 10^{-4} m^2/(V\text{-sec})$. Reduced ionic mobilities for flue gas compositions have been reported that are considerably larger than those reported for air. These values cover the range of $2.2\text{-}5.4 \times 10^{-4} m^2/(V\text{-sec})$. Some reported values of reduced ionic mobility for various gas compositions are given in Table 2. Since the ionic mobility has a strong influence on the electrical conditions through the current and electric field distributions, this is an important parameter in determining precipitator performance. A value of $3.0 \times 10^{-4} m^2/(V\text{-sec})$ should provide a representative value to use for flue gases emanating from coal-fired boiler applications. US is read in with a F8.0 format and must be left justified in columns 49-56.

(8) FPATH is a parameter which is used in the field charging equation and is dimensionless. FPATH represents the number of ionic mean free paths over which the momentum of the ions will persist and allow the ions to reach the surface of the particle even though the saturation charge has been reached. The effect of this parameter is to increase the saturation charge. FPATH normally should have a value in the range 0-2. It is recommended that FPATH be assigned a value of 1. FPATH is read in with a F8.0 format and must be left justified in columns 57-64.

(9) EBD is the electrical breakdown strength of the gas or the particulate layer in the region near the plate and is in units of V/m. The value of this parameter is a strong function of the resistivity of the collected

TABLE 2

REDUCED EFFECTIVE NEGATIVE ION MOBILITIES FOR VARIOUS GAS COMPOSITIONS

Gas Composition (Volume Percent)					Reduced Effective Ion Mobility (cm^2/V-sec)
N_2	CO_2	O_2	SO_2	H_2O	
				100.0	0.67 ± 0.17[a]
		100.0			2.46 ± 0.06[b]
	100.0				1.08 ± 0.03[b]
			100.0		0.35[c]
	(Laboratory Air)				1.03[d]
	(Laboratory Air)				1.26 - 1.96[e]
79.4	14.7	4.6	0.2	0.6	5.39[f]
73.5	13.6	4.2	0.2	8.4	2.93[f]
65.9	12.2	3.8	0.2	17.8	2.23[f]
71.0	11.2	3.7	0.0	14.0	2.35[f]
75.7	11.6	3.2	0.0	9.4	3.02[f]
75.1	11.5	3.2	0.1	9.9	2.74[f]
78.5	10.9	3.6	0.0	7.0	3.36[f]
78.3	19.8	3.6	0.1	7.0	2.67[f]
77.9	10.8	3.6	0.3	7.0	2.70[f]
77.6	10.7	3.7	0.7	7.0	2.43[f]

---

[a] J. J. Lowke and J. A. Rees, Australian J. Phys. 16, 447 (1963).

[b] E. W. McDaniel and H. R. Crane, Rev. Sci. Instru. 28, 684 (1959).

[c] E. W. McDaniel and M. R. C. McDowell, Phys. Rev. 114, 1028 (1959).

[d] B.Y.H. Liu, K. T. Whitby, and H.H.S. Yu, J. Appl. Phys. 38, 1592 (1967).

[e] J. Bricard, M. Cabane, G. Modelaine, and D. Vigla, Aerosols and Atmospheric Chemistry. Edited by G. M. Hidy, New York, New York, 27 (1972).

[f] H. W. Spencer, III, "Experimental Determination of the Effective Ion Mobility of Simulated Flue Gas." In Proceedings of 1975 IEEE-IAS Conference, September 28, 1975, Atlanta, Georgia.

particulate layer and the condition of the collection plates. At present, mathematical techniques which are based on physical principles do not exist for predicting the value of EBD under differing conditions. Thus, experimental data and prior experience must be used to choose appropriate values of EBD. In practical applications, EBD fails in the range of 2-15 kV/cm. A value of 2 kV/cm should provide a conservative estimate of EBD whereas a value of 15 kV/cm would in most cases provide the most optimistic value. The value of EBD is used whenever NVI = 2 and a voltage-current curve is generated. If the field at the plate exceeds the value of EBD at any point on the curve, a message to this effect is printed out with the V-I calculation terminating at the corresponding applied voltage and current density. These values of voltage and current are then used in the projection of precipitator performance. EBD is read in with a F8.0 format and must be right justified in columns 65-72.

(10) RHO is the resistivity of the collected particulate layer and is in units of ohm-cm. The resistivity to be used must be determined experimentally by either *in situ* or laboratory methods. RHO is used in the model only to estimate the average electric field in the collected particulate layer. It is not used to determine allowable electrical operating conditions. The effect of RHO on the allowable electrical operating conditions must be reflected in the input data for the operating voltages and currents. RHO is read in with a E8.2 format and must be right justified in columns 73-80.

The above data group has an overall format of (9F8.0, E8.2) and is contained on a single data card. This data set must be read in with each basic data set, i.e. when NDATA = 1.

The next data group which is read in depends on the value of NRAPD. If NRAPD is greater than 1, the following is a sequential listing of the variables in the next data group, along with the descriptions of the variables and the format specifications.

(1) ARD50(I) is an array containing the mass median diameters in μm for log-normal particle size distributions of the different rapping puff distributions which will be utilized in the model. The values of this variable are read in with a F4.0 format and must be left justified in columns 1-4, 9-12, 17-20, 25-28, 33-36, 41-44, 49-52, 57-60, 65-68, and 73-76.

(2) ARSIGM(I) is an array containing the geometric standard deviations for log-normal particle size distributions of the different rapping puff distributions which will

be utilized in the model. Values of ARD50(I) and ARSIGM(I) with the same index are used together to construct a log-normal particle size distribution. The values of this variable are read in with a F4.0 format and must be left justified in columns 5-8, 13-16, 21-24, 29-32, 37-40, 45-48, 53-56, 61-64, 69-72, and 77-80. ARSIGM(I) can not have a value less than 1.

The above variables must be read in for I=2 up to I=NRAPD where NRAPD can not exceed a value of 10. The overall format for this data group is (10(2F4.0)) and is contained on a single data card. If NRAPD=1, this data group is not read in. In this case, only one rapping puff particle size distribution will be considered where ARD50(1) = 6.0 in μm and ARSIGM(1) = 2.5. This case is built into the program and relates to experimental data discussed in Volume 1.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) ASNUCK(I) is an array containing different fractions of gas flow which bypass the electrified region in each baffled stage of the precipitator and/or different fractions of the mass collected in each stage of the precipitator which are reentrained due to factors other than rapping. The values of this variable are read in with a F4.0 format and must be left justified in columns 1-4, 13-16, 25-28, 37-40, 49-52, and 61-64 of the first two data cards in the group and in columns 1-4, 13-16, and 25-28 of the third data card in the group. ASNUCK(I) must lie in the range 0.0 to 1.0.

(2) AZIGGY(I) is an array containing different normalized standard deviations for the inlet velocity distribution of the gas flow. The values of this variable are read in with a F4.0 format and must be left justified in columns 5-8, 17-20, 29-32, 41-44, 53-56, and 65-68 of the first two data cards in the group and in columns 5-8, 17-20, and 29-32 of the third data card in the group. AZIGGY(I) must be equal to or greater than 0.0.

(3) AZNUMS(I) is an array containing the number of baffled stages in the precipitator. The values of this variable are read in with a F4.0 format and must be left justified in columns 9-12, 21-24, 33-36, 45-48, 57-60, and 69-72 of the first two data cards in the group and in columns 9-12, 21-24, and 33-36 of the third data card in the group. The values of AZNUMS(I) must be whole numbers.

The values of ASNUCK(I), AZIGGY(I), and AZNUMS(I) with the same index are used together to simulate one set of nonideal parameters and to produce one set of no-rap efficiencies. The values of I are determined by NONID which must have a value of at least 1 and can not exceed a value of 15. Thus, at least one set of these parameters must be read in. It is recommended that the user take the first set of these variables to be ASNUCK(1) = 0.00, AZIGGY(1) = 0.00, and AZNUMS(1) = actual number of stages so that efficiencies under ideal conditions will be obtained. In practical situations, a well-operating precipitator will have values of ASNUCK and AZIGGY of approximately 0.1 and 0.25, respectively.

The overall format for this data group is (6(3F4.0)) and the data group is contained on 3 or less cards. For NONID $\leq$ 6, 6<NONID $\leq$ 12, and 12<NONID < 15, the number of data cards necessary are 1, 2, and 3, respectively. This data group must be read in with each basic data set.

The next data group which is read in consists of a single array. The description of this array and its format specification are given below.

(1) ENDPT(I) is an array containing values of particle diameters corresponding to points on a curve of inlet mass cumulative percent versus particle diameter. The number of diameters that must be read in depends on the value of NENDPT which can not exceed a value of 21. The diameters must be inputted in order from smallest to largest in units of μm. The smallest diameter can not be less than 0.01 μm and the largest diameter can not exceed 1,000 μm. These diameters are used to construct particle size intervals and a particle size histogram. The midpoints between successive particle diameters constitute NENDPT-1 average particle diameters which are used in the program to characterize the different particle size bands. In constructing the particle diameters to be used in the calculations, it is recommended that greater resolution be built into the fine particle size range of 0.1-3.0 μm since the lower efficiencies are obtained in this size range. The values of ENDPT(I) are read in with a F8.0 format and must be left justified.

The overall format for this data group is (10F8.0) and the data group is contained on 3 or less data cards. For NENDPT $\leq$ 10, 10<NENDPT $\leq$ 20, and NENDPT = 21, the number of data cards necessary are 1, 2, and 3, respectively. This data group must be read in with each basic data set.

The next data group which is read in depends on the value of NDIST. If NDIST = 2, the following is a sequential listing of the variables in the next data group, along with the descriptions of the variables and the format specifications.

(1) D50	is the mass median diameter of a log-normal inlet particle size distribution and is in units of µm. The value of D50 must lie between 0.01 and 1,000 µm. The value of D50 is read in with a F8.0 format and must be left justified in columns 1-8.
(2) SIGMAP	is the geometric standard deviation of a log-normal inlet particle size distribution and is dimensionless. The value of SIGMAP must be equal to or greater than 1. The value of SIGMAP is read in with a F8.0 format and must be left justified in columns 9-16.

The program uses the values of D50 and SIGMAP to construct a log-normal particle size distribution over the range and size bands determined by the values of ENDPT(I). Any mass which is not in the size range determined by ENDPT(I) will be put into the size band with the largest midpoint. This must be done to ensure that the sum over all size bands of the percentage of total mass in each size band will equal 100%.

The above data group has an overall format of (2F8.0) and is contained on a single data card. This data set is not read in if NDIST = 1.

If NDIST = 1, the next data group which is read in consists of a single array. The description of this array and its format specification are given below.

(1) PRCU(I)	is an array containing values of cumulative percents corresponding to points on a curve of inlet mass cumulative percent versus particle diameter. The number of cumulative percents that must be read in depends on the value of NENDPT which can not exceed 21. The cumulative percents must match the particle diameters specified in the array ENDPT(I). The cumulative percents are inputted in units of %. The first value of PRCU(I) must be 0% and the last value must be 100%. The program determines the percentage by mass in each particle size band from the values contained in ENDPT(I) and PRCU(I). The user must supply values of PRCU(I) based on measured or known particle size information for the particular application under consideration. The values of PRCU(I) are read in with a F8.0 format and must be left justified.

The overall format for this data group is (10F8.0) and the data group is contained on 3 or less data cards. For $NENDPT \le 10$, $10 < NENDPT \le 20$, and $NENDPT = 21$, the number of data cards necessary are 1, 2, and 3, respectively. This data group is not read in if NDIST = 2.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) NUMSEC is the number of electrical sections in the direction of gas flow. The value of this variable is read in with an I2 format and must be right justified in columns 1-2.

(2) LSECT(I) is an array containing values of the number of incremental lengths to be taken in each electrical section in the direction of gas flow. These values are determined by the user with increasing values of I corresponding to electrical sections moving from the inlet to the outlet of the precipitator. The maximum number of electrical sections which can be accounted for in the program listed in Volume 1 is 10 ($I \le 10$). Also, the maximum total number of incremental lengths which can be taken is 45 ($\sum_I LSECT(I) \le 45$). Procedures for increasing the number of electrical sections and incremental lengths are discussed in Section 5. The values of this variable are read in with an I2 format and must be right justified.

The overall format for this data group is (I2, 10I2) and the data group is contained on a single data card. This data group must be read in with each basic data set.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) AS(NSECT) is the total collection plate area for a given electrical section and is in units of square feet. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

(2) VOS(NSECT) is the applied voltage in a given electrical section and is in units of volts. If NVI = 1, the value of VOS(NSECT) corresponds to a measured or known value. If NVI = 2, VOS(NSECT) corresponds to an applied voltage up to which a voltage-current curve will be calculated. Then, this applied voltage

along with the corresponding current will be used in the calculation of precipitator performance. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.

(3) TCS(NSECT) is the total current in a given electrical section and is in units of amperes. If NVI = 1, the value of TCS(NSECT) corresponds to a measured or known value. If NVI = 2, TCS(NSECT) has no meaning in terms of input data since it will be calculated in the program. In this case, the appropriate columns on the data card can be left blank or any arbitrary number can be entered. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.

(4) WLS(NSECT) is the total effective wire length in a given electrical section and is in units of feet. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.

(5) ACS(NSECT) is the corona wire radius in a given electrical section and is in units of inches. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.

(6) BS(NSECT) is the wire-to-plate spacing in a given electrical section and is in units of inches. The values of this variable are read in with an E11.4 format and must be right justified in columns 56-66.

(7) NWS(NSECT) is the number of discharge electrodes per given electrical section per gas passage and is dimensionless. The values of this variable normally should not exceed 20. If the values do exceed 20, use 20 in the program. These values are used to determine the number of terms in a series summation which determines the electrostatic electric field distribution and 20 terms are more than sufficient to reach convergence. The values of this variable are read in with an E11.4 format and must be right justified in columns 67-77.

(8) SYS(NSECT) is one-half of the wire-to-wire spacing in a given electrical section and is in units of inches. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

(9) VGS(NSECT)	is the total gas volume flow rate in a given electrical section and is in units of actual ft^3/min. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.
(10) VGASS(NSECT)	is the gas velocity in a given electrical section and is in units of ft/sec. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.
(11) TEMPS(NSECT)	is the gas temperature in a given electrical section and is in units of °F. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.
(12) PS(NSECT)	is the gas pressure in a given electrical section and is in units of atmospheres. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.
(13) VISS(NSECT)	is the gas viscosity in a given electrical section and is in units of kg/(m-sec). Table 3 gives values of viscosity for different temperatures and water contents for a gas composition whose components are those of air. This table provides values of viscosity which cover most cases found in practice although some extrapolation is necessary for those cases involving hot precipitators where temperatures are greater than 300°C. The values of this variable are read in with an E11.4 format and must be right justified in columns 56-66.
(14) LINCS(NSECT)	is the incremental length size which will be taken in a given electrical section and is in units of feet. If NVI = 1, LINCS(NSECT) should be given a value of approximately one foot although larger values can be used with some loss in accuracy in order to save computer run time. If NVI = 2, LINCS(NSECT) must be given a value equal as near as possible to the wire-to-wire spacing in order for the numerical procedure to be valid. In any case, the product of LSECT(NSECT) and LINCS(NSECT) must equal the total length of the given electrical section. The values of this variable are read in with an E11.4 format and must be right justified in columns 67-77.

The overall format for this data group is (7(E11.4)) and the data group is contained on two data cards. This data group must be read in with each basic data set.

TABLE 3. VALUES OF VISCOSITY FOR AIR AT VARIOUS TEMPERATURES AND WATER CONTENTS*

	Percent H_2O										
°C	0	1	2	3	4	5	6	7	8	9	10
10	1.767	1.758	1.748	1.739	1.730	1.721	1.712	1.702	1.693	1.684	1.675
20	1.810	1.801	1.792	1.783	1.774	1.765	1.755	1.746	1.737	1.728	1.719
30	1.854	1.844	1.835	1.826	1.817	1.808	1.799	1.790	1.780	1.771	1.762
40	1.900	1.887	1.878	1.869	1.860	1.850	1.841	1.832	1.823	1.814	1.805
50	1.938	1.929	1.920	1.911	1.902	1.892	1.883	1.874	1.865	1.856	1.847
60	1.979	1.970	1.961	1.952	1.943	1.934	1.925	1.916	1.907	1.898	1.888
70	2.020	2.011	2.002	1.993	1.984	1.975	1.966	1.957	1.948	1.939	1.930
80	2.059	2.050	2.042	2.033	2.024	2.015	2.006	1.997	1.988	1.979	1.970
90	2.099	2.090	2.081	2.072	2.063	2.054	2.046	2.037	2.028	2.019	2.010
100	2.137	2.129	2.120	2.111	2.102	2.093	2.085	2.076	2.067	2.058	2.049
110	2.175	2.167	2.158	2.149	2.140	2.132	2.123	2.114	2.105	2.097	2.088
120	2.213	2.204	2.195	2.189	2.178	2.169	2.161	2.152	2.143	2.135	2.126
130	2.250	2.241	2.232	2.224	2.215	2.207	2.198	2.189	2.181	2.172	2.164
140	2.286	2.277	2.269	2.260	2.252	2.243	2.235	2.226	2.218	2.209	2.201
150	2.321	2.313	2.304	2.296	2.288	2.279	2.271	2.262	2.254	2.245	2.237
160	2.356	2.348	2.339	2.331	2.323	2.315	2.306	2.298	2.289	2.281	2.273
170	2.390	2.382	2.374	2.366	2.358	2.349	2.341	2.333	2.325	2.316	2.308
180	2.424	2.416	2.408	2.400	2.392	2.383	2.375	2.367	2.359	2.351	2.343
190	2.457	2.449	2.441	2.433	2.425	2.417	2.409	2.401	2.393	2.385	2.377
200	2.489	2.482	2.474	2.466	2.458	2.450	2.442	2.434	2.426	2.418	2.410
210	2.521	2.513	2.506	2.498	2.490	2.482	2.475	2.467	2.459	2.451	2.443
220	2.552	2.545	2.537	2.530	2.522	2.514	2.507	2.499	2.491	2.483	2.476
230	2.583	2.575	2.568	2.560	2.553	2.545	2.538	2.530	2.523	2.515	2.507
240	2.613	2.606	2.598	2.591	2.583	2.576	2.569	2.561	2.554	2.546	2.539
250	2.642	2.635	2.628	2.621	2.613	2.606	2.599	2.592	2.584	2.577	2.570
260	2.671	2.664	2.657	2.650	2.643	2.636	2.628	2.621	2.614	2.607	2.600
270	2.699	2.692	2.685	2.678	2.671	2.664	2.657	2.650	2.643	2.636	2.629
280	2.727	2.720	2.713	2.706	2.700	2.693	2.686	2.679	2.672	2.665	2.658
290	2.754	2.747	2.740	2.734	2.727	2.720	2.714	2.707	2.700	2.694	2.687
300	2.780	2.773	2.767	2.761	2.754	2.748	2.741	2.734	2.728	2.721	2.715

X 10^{-5} kg/(m-sec)

---

*Calculations according to:
C.R. Wilke. A Viscosity Equation for Gas Mixtures. J. Chem. Phy., 18(4):517-519 (April, 1950).

The next data group which is read in depends on the value of NVI. If NVI = 2, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

(1) RFS(NSECT) is the roughness factor for the wires in a given electrical section and is dimensionless. In precipitation practice, if the wires are scratched or dirty but not completely coated with air, then the values of RFS(NSECT) lie in the range 0.5-1.0. A value of 1.0 corresponds to wires which are in perfect condition. The effect of decreasing the roughness factor is one of increasing the current that can be achieved at a given voltage level. If the wires are completely covered with dirt, then the effect may be one of increased wire diameter with a roughness superimposed. This situation would lead to compensating effects. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

(2) START1(NSECT) is the chosen initial current density at which the calculation of a voltage-current curve starts in a given electrical section and is in units of A/m^2. In generating the voltage-current curve, the current density increments in steps of START1 (NSECT) until a change is specified. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.

(3) START2(NSECT) is a chosen increment in current density which is used in place of START1(NSECT) when the JI1-th point on the voltage-current curve is reached and is in units of A/m^2. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.

(4) START3(NSECT) is a chosen increment in current density which is used in place of START2(NSECT) when the JI2-th point on the voltage-current curve is reached and is in units of A/m^2. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.

(5) VSTAR(NSECT) is an estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(NSECT) and is in units of volts. If VSTAR(NSECT) is close to the actual applied voltage, the calculation will be performed faster. However, whatever the choice of VSTAR (NSECT), it will not affect the accuracy of the

calculation. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.

The overall format for this data group is (7(E11.4)) and the data group is contained on a single data card. If NVI = 1, this data group is not read in.

The data input starting with AS(NSECT) above must be repeated for each electrical section of the precipitator, proceeding from the inlet to the outlet of the precipitator. Thus, the data group containing AS(NSECT) and possibly the data group containing RFS(NSECT) must be read in NUMSEC different times.

At this point, the basic data set has been entered into the program and precipitator performance will be projected based on the inputted data. The last card in the data section must have a 99 in columns 1-2. This causes the program to terminate normally.

CONSTRUCTION OF SHORTENED DATA SETS

Once the basic data set is processed, then all the parameters which are needed by the program to calculate precipitator performance are stored in memory. By using values of NDATA equal to 2, 3, or 4, shortened data sets can be entered after the basic data set in order to analyze the effects of particle size distribution, specific collection area, and electrical conditions on precipitator performance. In the shortened data sets, the values of a small number of variables which are stored in memory are changed to new values in order to produce a new set of data.

In each shortened data set, the first two data groups and data cards which are read in are the same as those discussed for the basic data set. The value of NDATA on the first data card determines the variables in memory that will be changed. The effects of particle size distribution on precipitator performance can be analyzed by setting NDATA = 2. In this case, the third data group which is read in depends upon the value of NDIST which is stored in memory. If NDIST = 2, an inlet mass median diameter (D50) and geometric standard deviation (SIGMAP) must be read in according to the same specifications discussed for the basic data set. If NDIST = 1, cumulative percents (PRCU(I)) corresponding to the particle sizes (ENDPT(I)) stored in memory must be read in according to the same specifications discussed for the basic data set. After the third data group is read in, the shortened data set is complete. By repeating this type of shortened data with different choices of D50 and SIGMAP or PRCU(I), the effects of particle size distribution can be analyzed with the use of only a few data cards.

The effects of specific collection area (SCA) on precipitator performance can be analyzed by setting NDATA = 3. In this case, the following is a sequential listing of the variables which are inputted in the third data group, along with the descriptions of the variables and the format specifications.

(1) VGS(I) is the total gas volume flow rate in a given electrical section and is in units of actual ft^3/min. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11, 23-33, and 45-55.

(2) VGASS(I) is the gas velocity in a given electrical section and is in units of ft/sec. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22, 34-44, and 56-66.

The overall format for this data group is (3(2E11.4)) and the data group is contained on 4 or less cards depending on the value of NUMSEC which is stored in memory. For NUMSEC $\leq$ 3, 3<NUMSEC $\leq$ 6, 6<NUMSEC $\leq$ 9, and NUMSEC = 10, the number of data cards necessary are 1, 2, 3, and 4, respectively.

After this data group is read in, the shortened data set is complete. By repeating this type of shortened data set with different choices of VGS(I) and VGASS(I), the effects of specific collection area can be analyzed with the use of only a few data cards.

The effects of applied voltage and current on precipitator performance can be analyzed by setting NDATA = 4. In this case, the following is a sequential listing of the variables which are inputted in the third data group, along with the descriptions of the variables and the format specifications.

(1) VOS(I) is the applied voltage in a given electrical section and is in units of volts. If the value of NVI stored in memory is 1, the value of VOS(I) corresponds to a measured or known value. If the value of NVI stored in memory is 2, VOS(I) corresponds to an applied voltage up to which a voltage-current curve will be calculated. Then, this applied voltage along with the corresponding current will be used in the calculation of precipitator performance. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11, 23-33, and 45-55.

(2) TCS(I) is the total current in a given electrical section and is in units of amperes. If the value of NVI stored in memory is 1, TCS(I) corresponds to a measured or known value. If the value of NVI stored in memory is 2, TCS(I) has no meaning in

terms of input data since it will be calculated in the program. In this case, the appropriate columns on the data cards can be left blank or any arbitrary number can be entered. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22, 34-44, and 56-66.

The overall format for this data group is (3(2E11.4)) and the data group is contained on 4 or less cards depending on the value of NUMSEC which is stored in memory. For $\text{NUMSEC} \leq 3$, $3 < \text{NUMSEC} \leq 6$, $6 < \text{NUMSEC} \leq 9$, and NUMSEC = 10, the number of data cards necessary are 1, 2, 3, and 4, respectively.

After this data group is read in, the shortened data set is complete. By repeating this type of shortened data set with different choices of VOS(I) and TCS(I), the effects of voltage and current can be analyzed with the use of only a few data cards.

By using the shortened data sets in different combinations and in a judicious order, much information can be generated with only a relatively few number of cards. Figure 27 contains a flow-chart which shows the logic involved in inputting the data and the data that are read in.

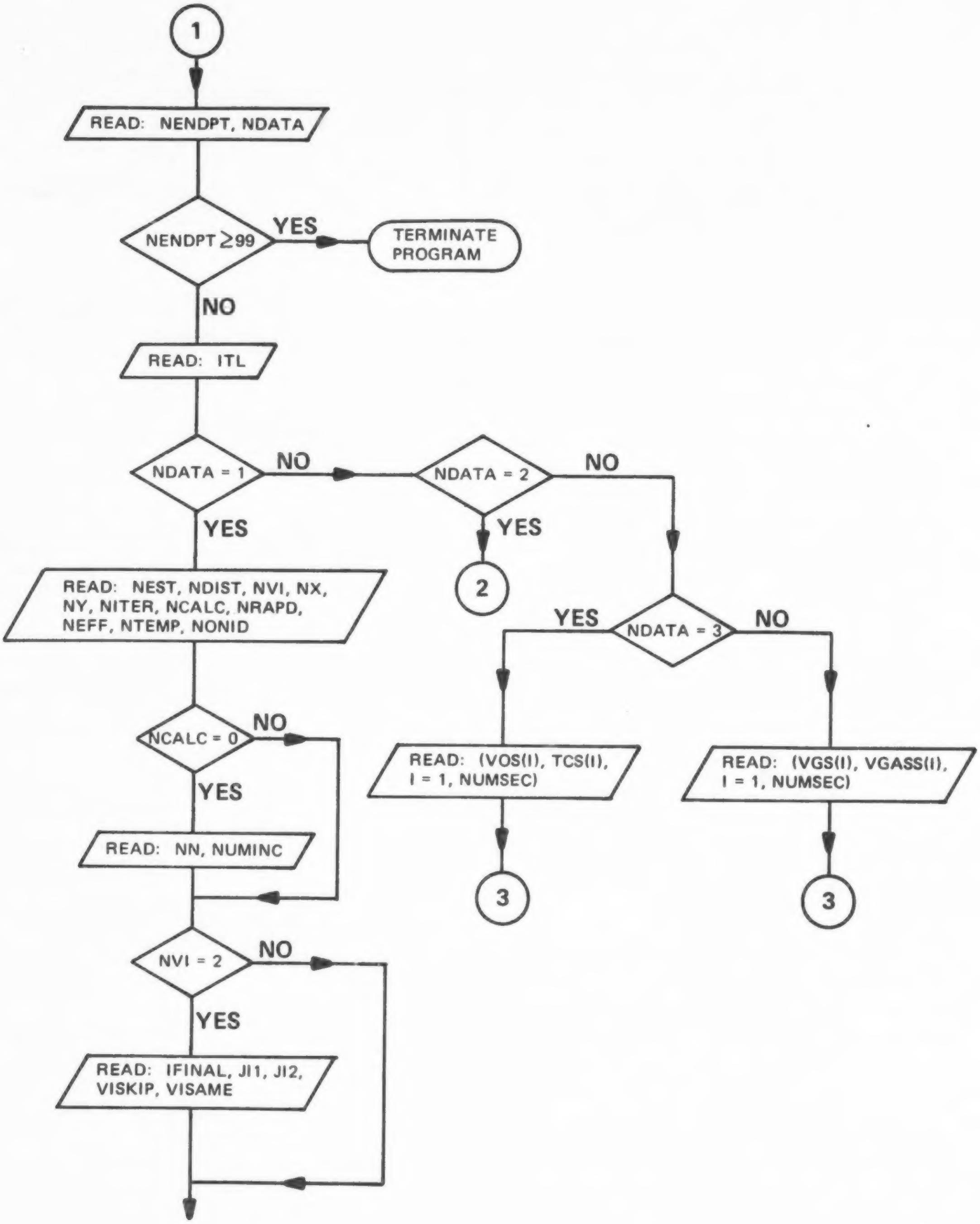

1
READ: NENDPT, NDATA
NENDPT ≥ 99
YES
TERMINATE PROGRAM
NO
READ: ITL
NDATA = 1
NO
NDATA = 2
NO
YES
2
YES
NDATA = 3
YES
NO
READ: NEST, NDIST, NVI, NX, NY, NITER, NCALC, NRAPD, NEFF, NTEMP, NONID
NCALC = 0
NO
YES
READ: NN, NUMINC
READ: (VOS(I), TCS(I), I = 1, NUMSEC)
READ: (VGS(I), VGASS(I), I = 1, NUMSEC)
3
3
NVI = 2
NO
YES
READ: IFINAL, JI1, JI2, VISKIP, VISAME

Figure 27. Flow chart for the input data logic (Sheet 1 of 2).

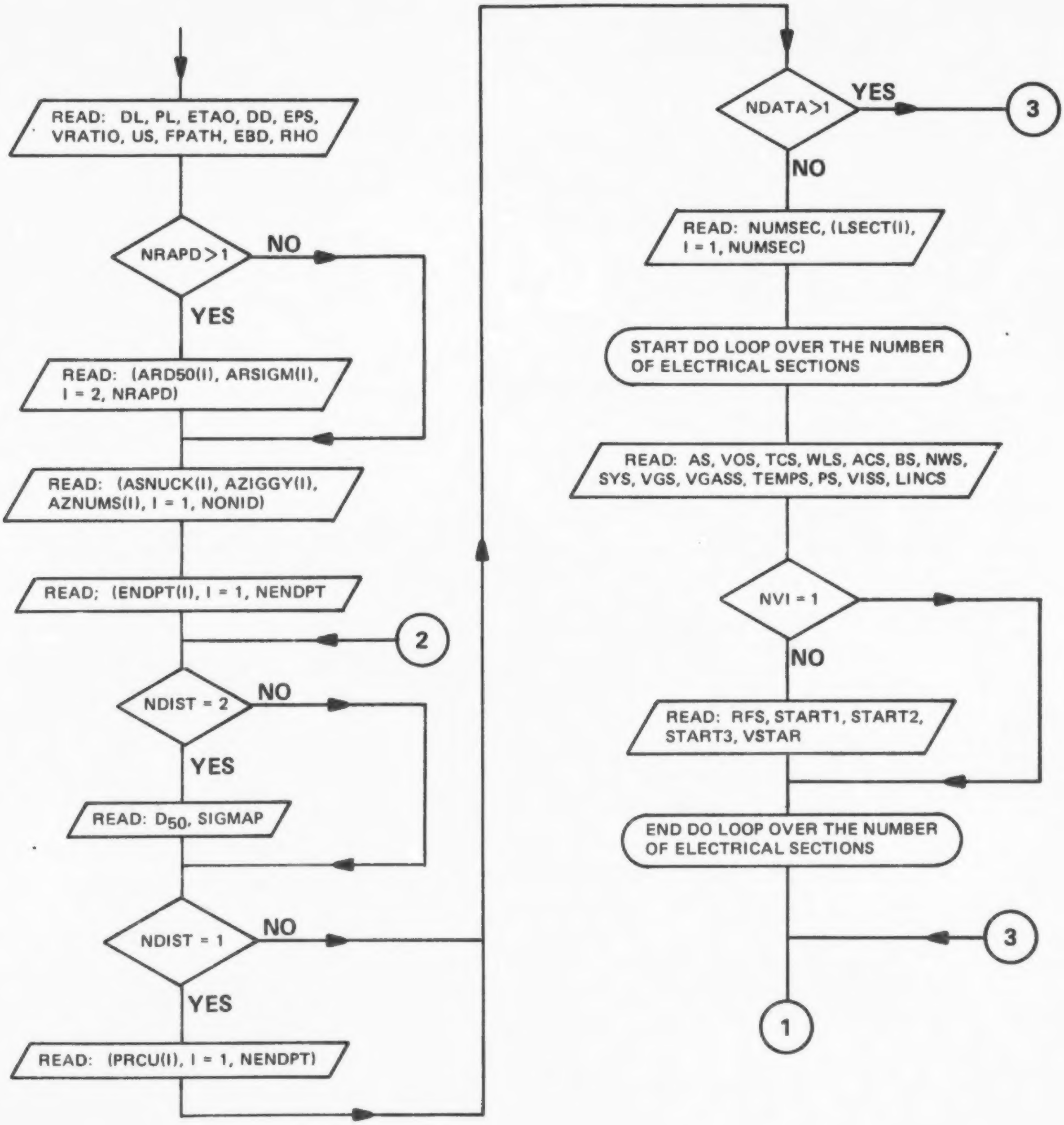

READ: DL, PL, ETAO, DD, EPS, VRATIO, US, FPATH, EBD, RHO
NRAPD>1
NO
YES
READ: (ARD50(I), ARSIGM(I), I = 2, NRAPD)
READ: (ASNUCK(I), AZIGGY(I), AZNUMS(I), I = 1, NONID)
READ; (ENDPT(I), I = 1, NENDPT
2
NDIST = 2
NO
YES
READ: D50, SIGMAP
NDIST = 1
NO
YES
READ: (PRCU(I), I = 1, NENDPT)
NDATA>1
YES
3
NO
READ: NUMSEC, (LSECT(I), I = 1, NUMSEC)
START DO LOOP OVER THE NUMBER OF ELECTRICAL SECTIONS
READ: AS, VOS, TCS, WLS, ACS, BS, NWS, SYS, VGS, VGASS, TEMPS, PS, VISS, LINCS
NVI = 1
NO
READ: RFS, START1, START2, START3, VSTAR
END DO LOOP OVER THE NUMBER OF ELECTRICAL SECTIONS
3
1

Figure 27. Flow chart for the input data logic (Sheet 2 of 2).

SECTION 9

MACHINE-DEPENDENT ASPECTS OF THE COMPUTER PROGRAM

The computer program, presented and discussed in this report, has been developed on a Digital Equipment Corporation (DEC) PDP 15/76 computer. By changing only two statements, the program has been executed successfully on an IBM 370/158 computer and on a UNIVAC 1100 computer. By changing the same two statements and certain output formating, the program has been executed successfully on a Control Data Corporation (CDC) 7600 computer. Although the program should compile successfully with only minor changes on most computers with a FORTRAN compiler, there are certain machine-dependent aspects of the program that should be discussed. These machine-dependent properties can be utilized to make the usage of the program more general and to extend the application of the program.

In order to use the program on most computers, the first two executable statements in the program must be changed. These statements define the input (read) and output (write) unit numbers. The value of the variable NREAD specifies the input unit number and the value of NPRNT specifies the outlet unit number. These two changes should normally be all the modifications which are necessary to allow successful compilation of the program. However, in order to execute the program on the CDC 7600 computer, it was also necessary to change single quotes to double quotes in output format statements. The approximate times required to compile the entire program on the DEC PDP 15/76, IBM 370/158, UNIVAC 1100, and CDC 7600 computers were 1575, 51, 95, and 5 seconds, respectively. Although these times can not be compared directly due to software differences and the fact that an overlay was necessary on the DEC PDP 15/76, they do give some indication of the relative compile times.

Once the program is compiled, it will execute provided that enough core is available to store the program. The total core requirements on the DEC PDP 15/76 are 86,334 octal words (36,060 decimal words) for the program plus 10,276 octal words (4,286 decimal words) for system software necessary to implement the program. Table 4 lists the various segments of the program and their core requirements.

TABLE 4. CORE REQUIREMENTS FOR VARIOUS SEGMENTS OF THE COMPUTER PROGRAM

	Octal Words	Decimal Words
RESIDENT CODE		
ESPM	11,113	4,683
CMAN	573	379
BLK1	502	322
BLK2	62	50
BLK3	16	14
BLK4	1	1
BLK5	15	13
BLK6	1,354	748
BLK7	3,410	1,800
BLK8	170	120
BLK9	74	60
BLK10	74	60
BLK11	53	43
BLK12	202	130
BLK13	702	450
BLK14	3	3
BLK15	71	57
BLK16	5	5
BLK17	2	2
BLK18	17	15
BLK19	57	47
BLK20	263	179
System Software	7,515	3,917

	Octal Words	Decimal Words
LINK1		
SPCHG1	407	263
EFLD1	13,663	6,607
LINK2		
SPCHG2	732	474
EFLD2	15,774	7,164
LINK3		
ADJUST	7,156	3,694
WADJST	610	392
CFIT	467	311
LNFIT	616	398
QTFE	160	112
LNDIST	1,567	887
PRTSUM	1,540	864
System Software	437	287
LINK4		
CHARGN	343	228
RATE	1,244	676
ARCCOS	200	128
ZERO	130	88
System Software	12	10
LINK5		
PRTINC	1,744	996
PRTCHG	1,562	882
PRTINP	5,113	2,635
CHGSUM	1,115	621
System Software	110	72

Due to the fact that the particular DEC PDP 15/76 which has been used to develop the program has only approximately 55,714 octal words (23,500 decimal words) of core that can be accessed at any given time, it was necessary to overlay subroutines in order to fit the program into core. The main program (ESPM) and subroutine CMAN were kept in resident core and the overlay was established by setting up the following five links:

LINK1 = SPCHG1, EFLD1

LINK2 = SPCHG2, EFLD2

LINK3 = ADJUST, WADJST, CFIT, LNFIT, QTFE, LNDIST, PRTSUM

LINK4 = CHARGN, RATE, ARCCOS, ZERO

LINK5 = PRTINC, PRTCHG, PRTINP, CHGSUM

With the above overlay, the required core is 55,633 octal words (23,451 decimal words) including system software. The core requirements were determined by the core utilized in resident core and the largest link (LINK2). In this particular overlay, LINK2 had 4,707 octal words (2,503 decimal words) of core which were not utilized. Also, the link table required an additional 323 octal words (211 decimal words) of core.

In order to get the program to execute on computers with small storage capacities, an overlay similar to the one discussed above may be possible. On computers with large memories such as the IBM 370/158, UNIVAC 1100, or CDC 7600, no such action is necessary.

Without changing the fundamental operations of the program, the dimensions of certain arrays can be decreased or increased if necessary. The dimensions of these arrays may be decreased in order to fit the program on a small computer or they may be increased to give greater flexibility on a large computer. In the version of the program presented in this report, the following quantities determine array sizes which may be changed:

- number of increments along the length of the precipitator
- number of particle size bands
- number of electrical sections in the direction of gas flow
- number of grid points used in the calculations of electrical conditions
- number of rapping puff particle size distributions

- number of sets of nonideal conditions of nonuniform gas velocity distribution and gas sneakage and/or particle reentrainment without rapping.

The above quantities have maximum values of 45, 20, 10, 225, 10, and 15, respectively.

The number of increments along the length of the precipitator that can be utilized can be changed by changing the dimension of DW and the dimension of the first subscript of XDC. DW appears in COMMON/BLK6/ and XDC appears in COMMON/BLK7/. COMMON/BLK6/ appears in the main program and subroutines PRTINP, CHGSUM, PRTINC, PRTCHG, ADJUST, and PRTSUM. COMMON/BLK7/ appears in the main program and subroutines SPCHG2 and PRTCHG. DW also appears in the dimension statement in the subroutine SPCHG1. If the storage capacity of the computer is large enough, the program should be modified to handle more than 45 increments. Although 120 increments should be sufficient to handle most cases, as many as 180 increments may be necessary in certain cases.

The number of particle size bands that can be utilized can be changed by changing the dimension of CHKSUM, DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, VOL, XNO, Q, WS, QSAT, OLDQ, OLDXNO, XDC, OLDQF, OLDQT, SOLDQF, SOLDQT, YY, RPCNT, DMDLD, WUNCOR, RDMDLD, CDMDLD, PCTOT, CPCTOT, WSL, PXS, EUNCOR, and AREA. In addition, changes must be made to those variables which depend on the number of particle diameters in the particle size histogram. These variables must have a dimension which is a value of 1 greater than those which depend on the number of size bands. These variables include PRCU, ENDPT, PRCUNR, RPRCU, PRCUC, Z, and Y. CHKSUM appears in the dimension statement in the main program. DIAM, ONO, DXS, XMV, PCNT, RAD, CCF, and PRCU appear in COMMON/BLK1/. VOL, XNO, Q, WS, QSAT, OLDQ, AND OLDXNO appear in COMMON/BLK6/. XDC appears in COMMON/BLK7/. ENDPT appears in COMMON/BLK11/. OLDQF, OLDQT, SOLDQF, and SOLDQT appear in COMMON/BLK20/. COMMON/BLK1/ appears in the main program and subroutines PRTINP, PRTCHG, and ADJUST. COMMON/BLK6/ and COMMON/BLK7/ appear in those locations previously designated. COMMON/BLK11/ appears in the main program and subroutines PRTINP, ADJUST, LNFIT, and LNDIST. COMMON/BLK20/ appears in the main program and subroutine CHGSUM. QSAT and XNO appear in the dimension statement in subroutine SPCHG1. XNO, RAD, CCF, OLDQ, and Q appear in the dimension statement in subroutine SPCHG2. YY appears in the dimension statement in subroutine PRTCHG. RPCNT, DMDLD, WUNCOR, RDMDLD, CDMDLD, PCTOT, CPCTOT, WSL, PXS, PRCUNR, RPRCU, PRCUC, and EUNCOR appear in the dimension statement in subroutine ADJUST. DIAM, ONO, and PXS appear in the dimension statement in subroutine WADJST. Z and Y appear in the dimension statement in subroutine CFIT. Z,Y, and PRCU appear in the dimension statement in subroutine LNFIT. AREA, PRCU, and PCNT appear in the dimension statement in subroutine LNDIST. In changing XDC, it is the second subscript which accounts for the maximum number of size bands which can be considered.

The number of electrical sections in the direction of gas flow that can be utilized can be changed by changing the dimension of LSECT, LINCS, PS, AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, RFS, START1, START2, START3, VSTAR, and NWS. LSECT, LINCS, and PS appear in COMMON/BLK2/. AS, VOS, TCS, WLS, ACS, BS, SYS, VGS, VGASS, TEMPS, VISS, RFS, START1, START2, START3, and VSTAR appear in COMMON/BLK6/. NWS appears in COMMON/BLK19/. COMMON/BLK2/ appears in the main program and in subroutines PRTINP and ADJUST. COMMON/BLK6/ appears in those locations previously designated. COMMON/BLK19/ appears in the main program and subroutines PRTINP, PRTCHG, and ADJUST. LSECT appears in the dimension statement in subroutine SPCHG1.

The number of grid points that can be utilized in the calculation of electrical conditions can be changed by changing the dimensions of VCOOP, RHO, EX, OLDRO, OLDV, CDNSTY, V, EY, EAVGS, CHFIDS, ECOLLS, EAVG, CHFID, and ECOLL. VCOOP appears in COMMON/BLK13/. EAVG and CHFID appear in COMMON/BLK8/. ECOLL appears in COMMON/BLK9/. COMMON/BLK3/appears in the main program and subroutines CMAN, EFLD1, and EFLD2. COMMON/BLK8/ appears in the main program and subroutines SPCHG2, EFLD2, and PRTCHG. COMMON/BLK9/ appears in the main program and subroutine EFLD2. RHO, EX, OLDRO, OLDV, CDNSTY, V, and EY appear in the dimension statement in subroutine EFLD1. RHO, EX, OLDRO, OLDV, CDNSTY, V, EY, EAVGS, CHFIDS, and ECOLLS appear in the dimension statement in subroutine EFLD2. VCOOP, RHO, EX, OLDRO, OLDV, CDNSTY, V, and EY are doubly subscripted variables with the first subscript referring to the number of grid points in the direction perpendicular to the gas flow and the second subscript referring to the number of grid points in the direction parallel to the gas flow. EAVG, CHFID, ECOLL, EAVGS, CHFIDS, and ECOLLS are singly subscripted variables whose dimension must be a value of two less than twice the dimension of the second subscript in the variables VCOOP, RHO, EX, OLDRO, OLDV, CDNSTY, V, and EY.

The number of rapping puff particle size distributions that can be utilized can be changed by changing the dimension of ARD50 and ARSIGM. ARD50 and ARSIGM appear in COMMON/BLK12/. COMMON/BLK12/ appears in the main program and in subroutines PRTINP and ADJUST.

The number of sets of nonideal conditions of nonuniform gas velocity distribution and gas sneakage and/or particle reentrainment without rapping that can be utilized can be changed by changing the dimension of ASNUCK, AZIGGY, and AZNUMS. These variables appear in COMMON/BLK12/. COMMON/BLK12/ appears in those locations previously designated.

If any changes are made that affect arrays, it should be pointed out that these changes will also affect the limitations on the input data discussed in Section 8. The limitations on the input data discussed previously are only applicable to the version of the program presented in Appendix C of Volume 1. If changes are made, new limitations on the input data must be established.

REFERENCES

1. Gooch, J. P., J. R. McDonald, and S. Oglesby, Jr. A Mathematical Model of Electrostatic Precipitation. EPA-650/2-75-037, U.S. Environmental Protection Agency, Raleigh Durham, North Carolina, 1975. pp. 78-79.
2. Gooch, J. P., and J. R. McDonald. Mathematical Modelling of Fine Particle Collection by Electrostatic Precipitation. Atmospheric Emissions and Energy-Source Pollution, AICHE Symposium Series, 73(165):146, 1977.
3. Gooch, J. P., and J. R. McDonald. Mathematical Modelling of Fine Particle Collection by Electrostatic Precipitation. Conference on Particulate Collection Problems in Converting to Low Sulfur Coals, Interagency Energy-Environment Research and Development Series. EPA-600/7-76-016, U.S. Environmental Protection Agency, 1976. 68 pp.
4. Gooch, J. P., and G. H. Marchant, Jr. Electrostatic Precipitator Rapping Reentrainment and Computer Model Studies. Final Draft Report prepared for the Electric Power Research Institute, 1977.
5. Pauthenier, M., and M. Moreau-Hanot. Charging of Spherical Particles in an Ionizing Field. J. Phys. Radium, 3(7):590-613, 1932.
6. White, H. J. Particle Charging in Electrostatic Precipitation. Trans. Amer. Inst. Elec. Eng. Part 1, 70:1186-1191, 1951.
7. Murphy, A. T., F. T. Adler, and G. W. Penney. A Theoretical Analysis of the Effects of an Electric Field on the Charging of Fine Particles. Trans. Amer. Inst. Elec. Eng., 78:318-326, 1959.
8. White, H. J. Industrial Electrostatic Precipitation. Addison-Wesley, Reading, Massachusetts, 1963. p. 157.
9. Fuchs, N. A. The Mechanics of Aerosols. Chapter 2. Macmillan, New York, 1964.
10. White, H. J. Reference 8, pp. 166-170.
11. White, H. J. Reference 8, pp. 185-190.

12. Penney, G. W., and S. Craig. Pulsed Discharges Preceding Sparkover at Low Voltage Gradients. AIEE Winter General Meeting, New York, 1961.

13. Pottinger, J. F. The collection of Difficult Materials by Electrostatic Precipitation. Australian Chem. Process Eng., 20(2):17-23, 1967.

14. Spencer, H. W. Electrostatic Precipitators: Relationship Between Resistivity, Particle Size, and Sparkover. EPA-600/2-76-144, U.S. Environmental Protection Agency, Raleigh Durham, North Carolina, 1976.

15. Bickelhaupt, R. E. Surface Resistivity and the Chemical Composition of Fly Ash. APCA Journal, 25(2):148-152, 1975.

16. Bickelhaupt, R. E. Volume Resistivity - Fly Ash Composition Relationship. Environmental Sc. & Tech., 9(4):336-342, 1975.

17. Selle, S. J., L. L. Hess, and E. A. Sondreal. Western Fly Ash Composition as an Indicator of Resistivity and Pilot ESP Removal Efficiency. Paper 75-02.5 presented at the 68th Meeting of the Air Pollution Control Association, Boston, Massachusetts, 1975.

18. Contract No. 68-02-2114, Task IV between E.P.A. and So.R.I.

19. White, H. J. Reference 8, pp. 238-293.

20. Preszler, L., and T. Lajos. Uniformity of the Velocity Distribution Upon Entry into an Electrostatic Precipitator of a Flowing Gas. Staub Reinhalt. Luft (in English), 32(11):1-7, 1972.

21. Spencer, H. W. A Study of Rapping Reentrainment in a Nearly Full Scale Pilot Electrostatic Precipitator. EPA-600/2-76-140, U.S. Environmental Protection Agency, Raleigh Durham, North Carolina, 1976.

22. Leutert, G., and B. Böhlen. The Spatial Trend of Electric Field Strength and Space Charge Density in Plate-Type Electrostatic Precipitators. Staub, 32(7):27, 1972.

23. McDonald, J. R., W. B. Smith, H. W. Spencer, and L. E. Sparks. A Mathematical Model for Calculating Electrical Conditions in Wire-Duct Electrostatic Precipitation Devices. J. Appl. Phys., 48(6):2231-2246, 1977.

24. Smith, W. B., and J. R. McDonald. Development of a Theory for the Charging of Particles by Unipolar Ions. J. Aerosol Sci., 7:151-166, 1976.

25. Hewitt, G. W. The Charging of Small Particles for Electrostatic Precipitation. AIEE Trans., 76:300, 1957.

26. Oglesby, S., and G. B. Nichols. A Manual of Electrostatic Precipitator Technology: Part I, Fundamentals. NTIS PB 196380, APTD 0610, National Air Pollution Control Administration, Cincinnati, Ohio, 1970. pp. 57-66.

27. McDonald, J. R. Mathematical Modelling of Electrical Conditions, Particle Charging, and the Electrostatic Precipitation Process. Ph.D. Dissertation, Physics Dept., Auburn University, Auburn, Alabama, 1977. pp. 47-54.

28. Cooperman, P. The Dependence of the Electrical Characteristics of Duct Precipitators on Their Geometry. Unpublished Report, Research Corp., 1952.

29. Flügge, S. Handbuch der Physik (Handbook of Physics). Springer-Verlay, Berlin, 16:248 ff., 1958.

30. Burns, K. J., and P. J. Lawrenson. Analysis and Computation of Electrical and Magnetic Field Problems. Pergamon Press, Oxford, 1963. p. 251 ff.

31. Ralston, A., and H. S. Wilf. Mathematical Methods for Digital Computers. Wiley and Sons, Inc., New York, 1960. p. 144 ff.

32. Young, D. Iterative Methods for Solving Partial Difference Equations of Elliptic Type. Trans. Amer. Math. Soc., 76:92-111, 1954.

33. Nielsen, K. L. Methods in Numerical Analysis, 3rd Edition. The MacMillan Company, New York, 1964. pp. 236-239.

34. Nielsen, K. L. Reference 32, p. 122.

35. CRC Standard Mathematical Tables. Fourteenth Edition, edited by Samuel M. Selby, The Chemical Rubber Co., Cleveland, Ohio, 1965. p. 409.

36. Murphy, A. T. Charging of Particles by Random Motion of Ions in an Electric Field. Ph.D. Dissertation, Dept. of Electrical Engineering, Carnegie Institute of Technology, Pittsburgh, Pa., 1957. p. 59.

37. Hildebrand, F. B. Introduction to Numerical Analysis. McGraw-Hill, Inc., New York, 1956. p. 75.

38. Hastings, C., Jr. Approximations for Digital Computers. Princeton University Press, Princeton, New Jersey, 1955. p. 192.

39. Bevington, P. R. Data Reduction and Error Analysis for the Physical Sciences. McGraw-Hill, Inc., New York, 1969. pp. 99-122.

40. Spencer, H. W. Experimental Determination of the Effective Ion Mobility of Simulated Flue Gas. In: Proceedings of 1975 IEEE-IAS Conference, Atlanta, Georgia, 1975.

41. White, H. J. Reference 8, p. 92.

APPENDIX A

DEVELOPMENT OF NEW PROCEDURE FOR DETERMINING SPACE CHARGE EFFECTS

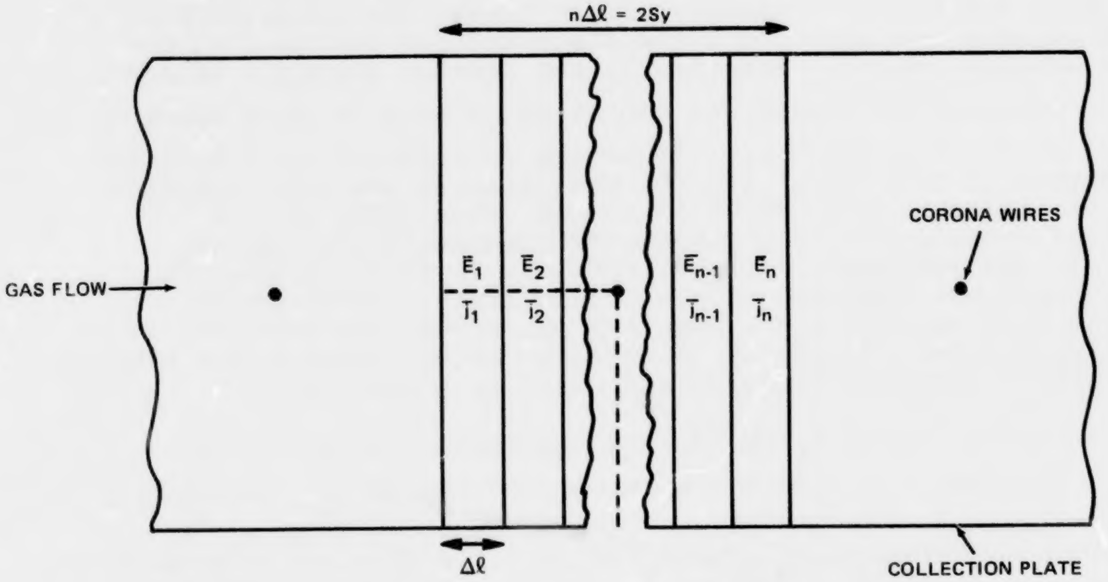
When particles are introduced into a precipitator, the mechanisms of particle charging and particle collection come into play. In order to account for the dynamics of these mechanisms, it is necessary to determine the ion density and electric field distributions to which the particles will be subjected. These are obtained for the flue gas without particles by calculating a voltage-current curve using the technique discussed earlier. The reliability of this calculation will depend to a large extent on the choice of ion "effective mobility", used to represent clean flue gas, and the condition of the discharge electrodes. Representative values of ion "effective mobility" should be obtained from in situ measurements, or laboratory measurements made on gases of similar composition in the proper environment.[40] The condition of the discharge wires with regards to roughness is accounted for by a roughness factor f.[41] This factor normally lies in the range of 0.5-1.0 and has a significant effect on the space charge density near the discharge electrode.

For the desired operating voltage and current which are obtained from the "clean" voltage-current curve, the corresponding current density and electric field distributions are used to determine average current densities $\bar{J}_\ell$ and average electric fields $\bar{E}_\ell$ for n incremental lengths $\Delta\ell$ contained in wire-to-wire spacings centered on the wires. This formulation is depicted in Figure 28. The incremental lengths $\Delta\ell$ are the same size as the grid spacings in the direction of gas flow used in the calculation of the electrical conditions. Using symmetry considerations, we can obtain all the information shown in Figure 28 from calculations based on the area enclosed in the dashed lines. Although this formulism does not provide a complete positional description, it does allow for the effects of nonuniform current density and electric field on particle charging and particle collection.

The values of the $\bar{J}_\ell$ and $\bar{E}_\ell$ and the designated particle charging equation are used to calculate the charge $q_{i,\ell}$ on each particle size i at the end of the ℓ-th incremental length. In the regions midway between wires, the particle charging rate will be lowest due to lower values of $\bar{J}_\ell$ and $\bar{E}_\ell$. As uncollected particles move toward regions directly between a wire and the plate, the charging rate will tend to increase due to higher values of $\bar{J}_\ell$ and $\bar{E}_\ell$.

The average charge density $\bar{\rho}_\ell$ due to the total particulate loading in the ℓ-th incremental length is given by

$$\bar{\rho}_\ell = \sum_i \bar{\rho}_{i,\ell} = \sum_i x_{i,\ell}\, q_{i,\ell} \quad , \qquad (95)$$



nΔℓ = 2Sy
GAS FLOW
CORONA WIRES
$\bar{E}_1$
$\bar{E}_2$
$\bar{j}_1$
$\bar{j}_2$
$\bar{E}_{n-1}$
$\bar{E}_n$
$\bar{j}_{n-1}$
$\bar{j}_n$
Δℓ
COLLECTION PLATE

n = NUMBER OF INCREMENTAL LENGTHS CONTAINED IN ONE WIRE-TO-WIRE SPACING

Sy = ONE-HALF THE WIRE-TO-WIRE SPACING

Δℓ = INCREMENTAL LENGTH

$\bar{E}_\ell$ = AVERAGE ELECTRIC FIELD IN ℓ-TH INCREMENTAL LENGTH

$\bar{j}_\ell$ = AVERAGE CURRENT DENSITY IN ℓ-TH INCREMENTAL LENGTH

Figure 28. Nomenclature used in the procedure which determines particulate space charge effects.

where $\bar{\rho}_{i,\ell}$ = average charge density for the i-th particle size at the end of the ℓ-th incremental length (coul/m^3), and

$X_{i,\ell}$ = number of particles per unit volume of gas of the i-th particle size entering the ℓ-th incremental length (m^{-3}).

A weighted particulate mobility $\bar{b}_\ell$ due to all particles in the ℓ-th incremental length can be defined as

$$\bar{b}_\ell = \frac{\sum_i (X_{i,\ell}\, q_{i,\ell}\, C_i)/(6\pi\mu a_i)}{\sum_i X_{i,\ell}}$$

$$= \frac{\sum_i (\bar{\rho}_{i,\ell}\, C_i)/(6\pi\mu a_i)}{X_\ell} \quad , \tag{96}$$

where C_i = Cunningham correction factor for the i-th particle size,

μ = viscosity of the gas (kg/m-sec),

a_i = radius of the i-th particle size (m), and

X_ℓ = total number of particles per unit volume of gas entering the ℓ-th incremental length (m^{-3}).

The average ionic charge density $\bar{\rho}'_\ell$ with a mass loading in the ℓ-th incremental length is obtained from

$$\bar{\rho}'_\ell = \frac{\bar{J}_\ell}{b' E_\ell} - (\rho_\ell - \rho_{\ell-1})$$

$$= \bar{\rho}''_\ell - \Delta\bar{\rho}_\ell \quad , \tag{97}$$

where b' = molecular ion "effective mobility" (m^2/V-sec),

$\bar{\rho}''_\ell$ = average ionic charge density without mass loading in the ℓ-th incremental length (coul/m^3), and

$\Delta\bar{\rho}_\ell$ = average charge density shifted from molecular ions to particles in the ℓ-th incremental length (coul/m^3).

An effective mobility b^e_ℓ due to both ions and particles in the ℓ-th incremental length is found from

$$b^e_\ell = \frac{b' \bar{\rho}'_\ell + \bar{b}_\ell \bar{\rho}_\ell}{\bar{\rho}'_\ell + \bar{\rho}_\ell} \quad . \tag{98}$$

Since a certain number of particles will be removed from the gas stream in the ℓ-th incremental length, it is necessary to calculate collection efficiencies for the different particle sizes. The collection efficiencies are calculated using equation (5), where the migration velocities are calculated from

$$w_{i,\ell} = \frac{q_{i,\ell}\, \bar{E}^p_\ell\, C_i}{6\pi a_i \mu} \tag{99}$$

and $\bar{E}^p_\ell$ is the average electric field at the collection plate in the ℓ-th incremental length. Thus, the size distribution entering the $(\ell+1)$-th incremental length is obtained from

$$X_{i,\ell+1} = (1 - \eta_{i,\ell})\, X_{i,\ell} \quad . \tag{100}$$

An "effective mobility" b^e_ℓ is calculated for each of n successive incremental lengths over a total length equal to the wire-to-wire spacing. Then, the "average effective mobility" b^e for ions and particles over a length equal to the wire-to-wire spacing is calculated from

$$b^e = \frac{1}{n} \sum_{\ell=1}^{n} b^e_\ell \quad . \tag{101}$$

The value of b^e is used to generate a voltage-current curve for the particular wire-to-wire length under consideration in order to describe the effect of particles on the electrical conditions. In this calculation, it is assumed that over several wire-to-wire spacings symmetry in the electric field and space charge density distribution is essentially preserved. Also, strictly speaking, it is not valid to generate the entire voltage-current curve with a constant value of b^e when particles are present. This is because b^e is a function of applied voltage and current density since it depends on particle charging and particle collection. However, at the operating applied voltage, the correct current density will be predicted and, in fact, the entire voltage-current curve will be approximately correct since b^e normally will not vary enough over practical voltage ranges to produce significant differences. In any case, the generation of a voltage-current curve can be viewed as a systematic procedure for searching for the current density that would exist at the operating applied voltage.

In lieu of using the time-consuming, voltage-current calculation, it is possible to estimate the operating current density for a given applied voltage from a simple relationship, provided certain considerations are made. If particles are introduced into a precipitator and the applied voltage is held fixed, then the current density at any location and the effective charge carrier mobility will be lowered. Since the product of total space charge density and electric field strength at any location is equal to the ratio of current density to effective mobility, the product tends to remain constant. If it is assumed that the limited regions of ionization near the corona electrodes are unchanged by the presence of particles, then, even though charge is transferred to particles in these regions, the space charge density and electric field near a wire will both remain essentially constant. Thus,

$$\bar{j}_{w/b'} = \bar{j}'_{w/b^e} \quad , \tag{102}$$

where

$\bar{j}_w$ = average current density near the wire without particles (A/m^2), and

$\bar{j}'_w$ = average current density near the wire with particles (A/m^2).

The average current density at the wire is related to the average current density at the plate by

$$\bar{j}_w = (A'_p/A_w)\bar{j}_p \quad , \tag{103}$$

where

A_p' = collection plate area receiving current from a single wire (m^2),

A_w = surface area of a single wire (m^2), and

$\bar{j}_p$ = average current density at the collection plate without particles (A/m^2).

Using equations (102) and (103),

$$\bar{j}_p' = (b^e/b')\bar{j}_p \quad , \tag{104}$$

where $\bar{j}_p'$ (A/m^2) is the average current density at the collection plate with particles present. Equation (104) provides a simple way to estimate the reduction in current density at the plate due to the presence of particles.

The operating current densities are determined for successive wire-to-wire spacings throughout the length of the precipitator. Since the space charge scheme incorporates the dynamics of the precipitation process, particle collection efficiencies are predicted as well as operating voltages and current densities. In this scheme, no estimate of overall mass efficiency is necessary as is the case in the procedure using equation (16) and this is advantageous in designing a new precipitator.

Figures 29-35 show some theoretical trends predicted by using the new space charge scheme. In these figures, the ion "effective mobility", at standard temperature and pressure, and the roughness factor were taken to be 2.2×10^{-4} $m^2/V\cdot sec$ and 1.0, respectively. The parameters used in the calculations are typical of full-scale, cold-side precipitators. The electrode geometry consists of plate-to-plate and wire-to-wire spacings of 22.86 cm and a wire radius of 0.138 cm. The inlet particle size distribution (MMD = 25 μm, σ_p = 2.8) is characteristic of fly ash obtained from the combustion of Eastern coal.

Figures 29-31 show the variation of average current density along the length of the precipitator for different inlet mass loadings, specific collection areas, and voltage levels. The different specific collection areas were obtained by leaving the plate area fixed and varying the volume flow rate. Near the inlet of the precipitator, the curves show a minimum in the average current density at the plate. This behavior might be expected since the "effective mobility" should initially decrease due to the charging process and then, as the charging process slows down

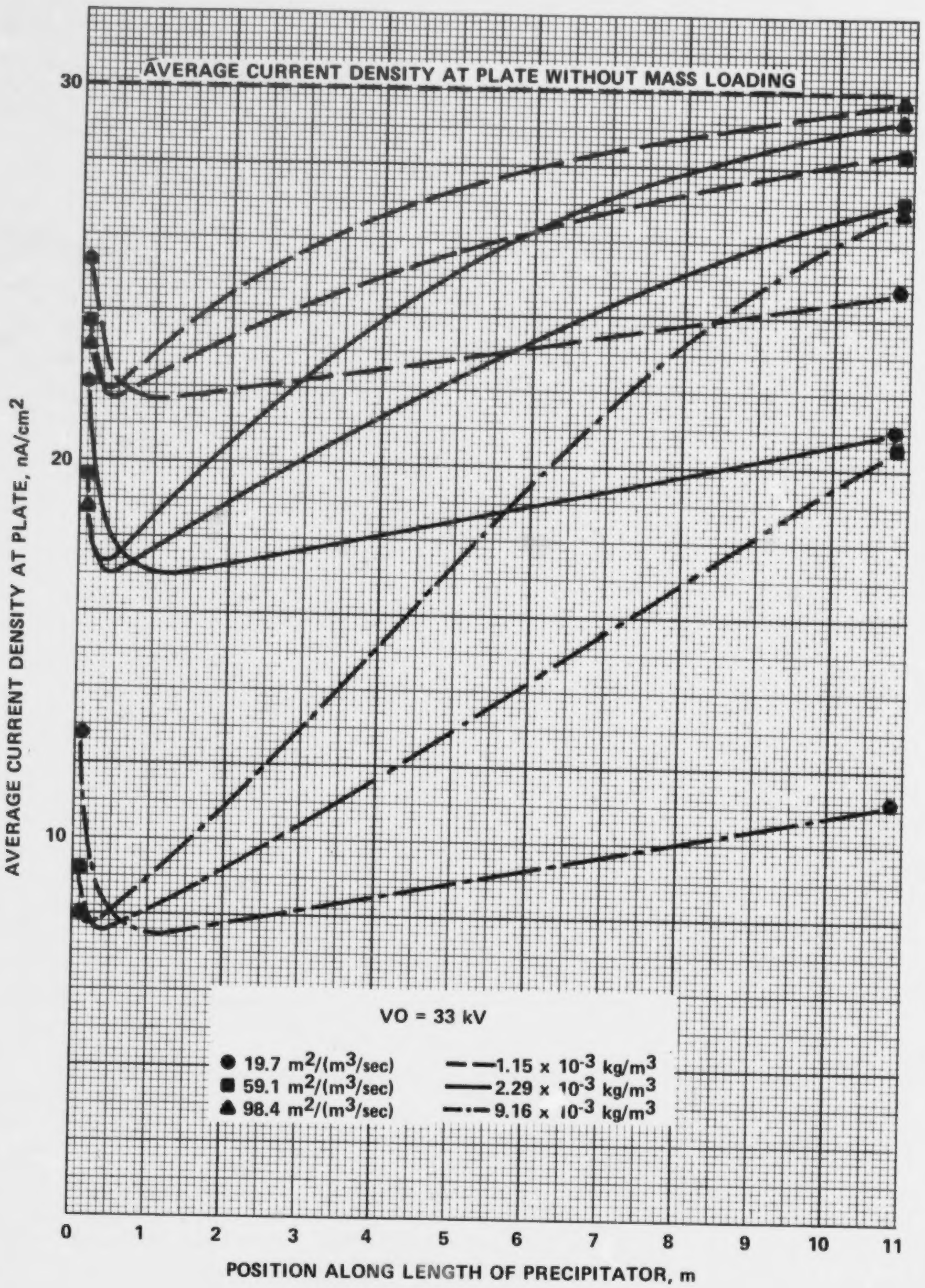


Figure 29. *Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 33 kV.*

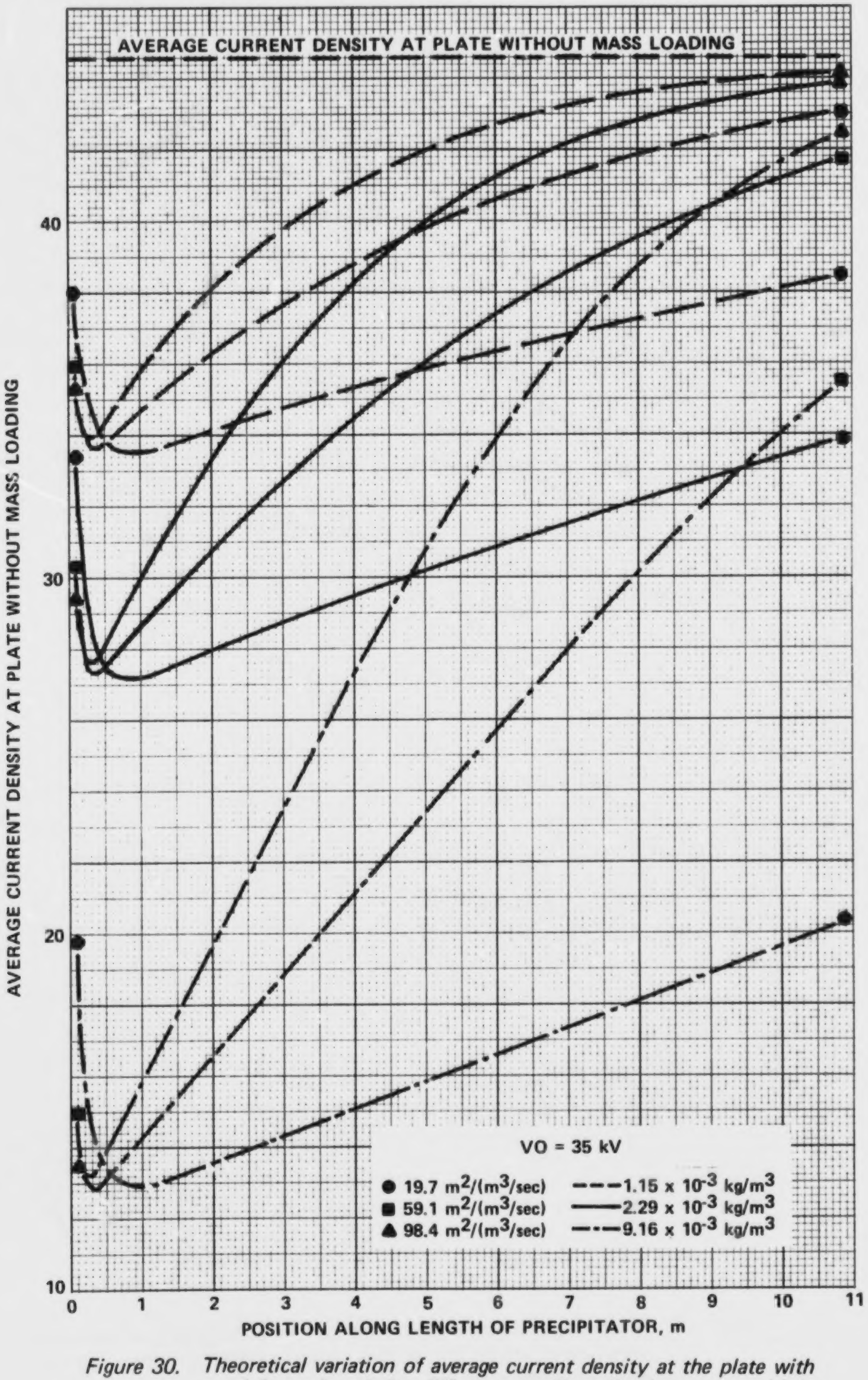


Figure 30. *Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 35 kV.*

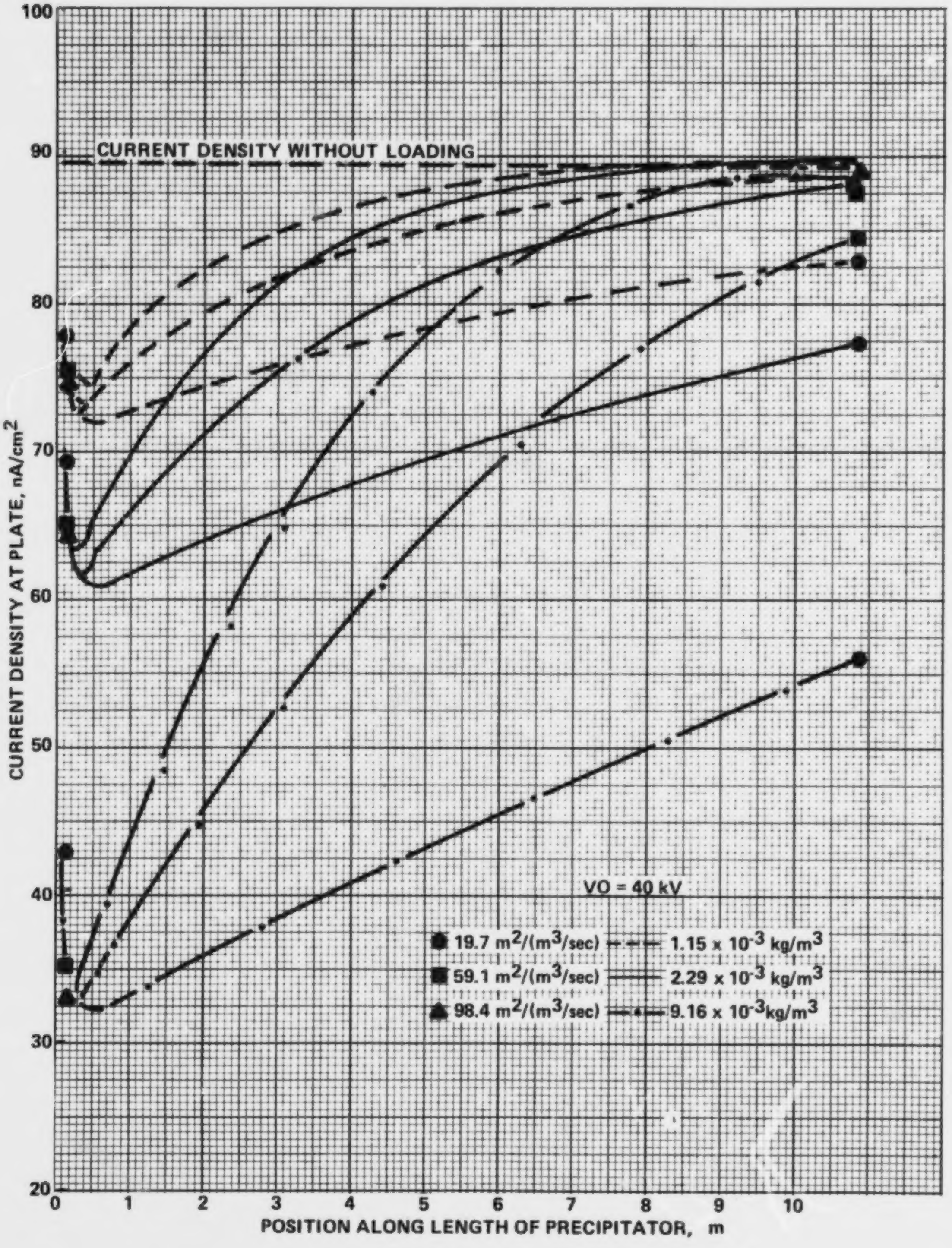


Figure 3l. Theoretical variation of average current density at the plate with precipitator length for different specific collection areas and inlet mass loadings at 40 kV.

and charged particles are collected, it should reach a minimum and begin to increase.

Figures 32-35 show results obtained by dividing the precipitator into four electrical sections and calculating voltage-current characteristics for each section. The calculations are for an inlet mass loading of 9.16×10^{-3} kg/m^3 and a range of specific collection areas. The curves indicate the effect of particulate space charge on the operating voltage-current characteristics in different electrical sections of the precipitator.

In Figure 36, the predictions of the model with the new space charge scheme are compared with field test data from a full-scale precipitator with wire-duct geometry and the predictions of the model with the old space charge scheme. The figure also shows the effect of the roughness factor in determining current density and collection efficiency. The results indicate that the condition of the wire plays a very important role in the theoretical determination of voltage-current characteristics. A roughness factor of 0.9 yields an average operating current density of 25 nA/cm^2 at the operating voltage of 33 kV. The actual average operating current density was 20 nA/cm^2. The roughness factor could be adjusted to yield 20 nA/cm^2 but this refinement would probably not be meaningful due to the uncertainty in the ion mobility of the flue gas which was taken to be 2.2×10^{-4} m^2/V·sec at standard temperature and pressure. A roughness factor of 0.9 would not be unreasonable since the electrodes were known to be in good condition at the time of the test. If the wires are specked with dirt or scratched, then it is appropriate to use a roughness factor. However, if the wires are uniformly coated with a layer of dirt, then the effect is one of increasing the radius of the discharge electrode which has a different effect on the voltage-current characteristics.

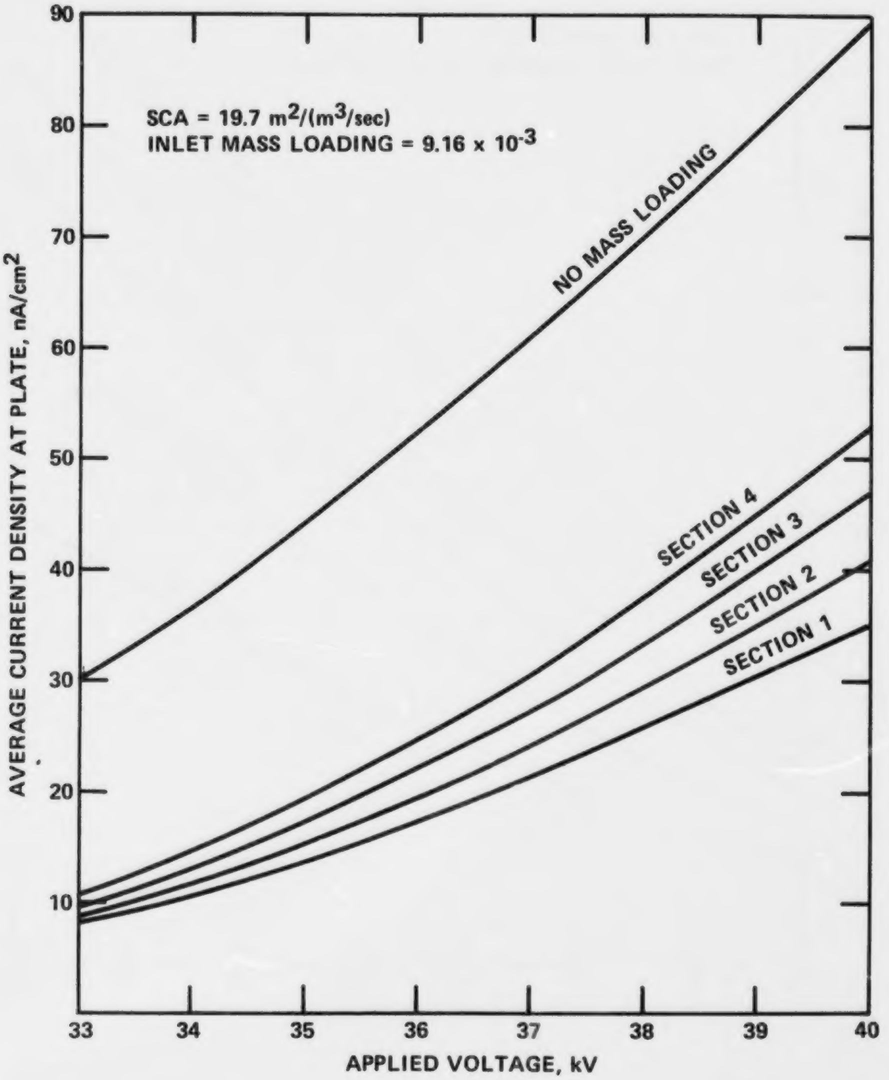


Figure 32. *Theoretical voltage-current curves for a specific collection area of 19.7 $m^2/(m^3/sec)$.*

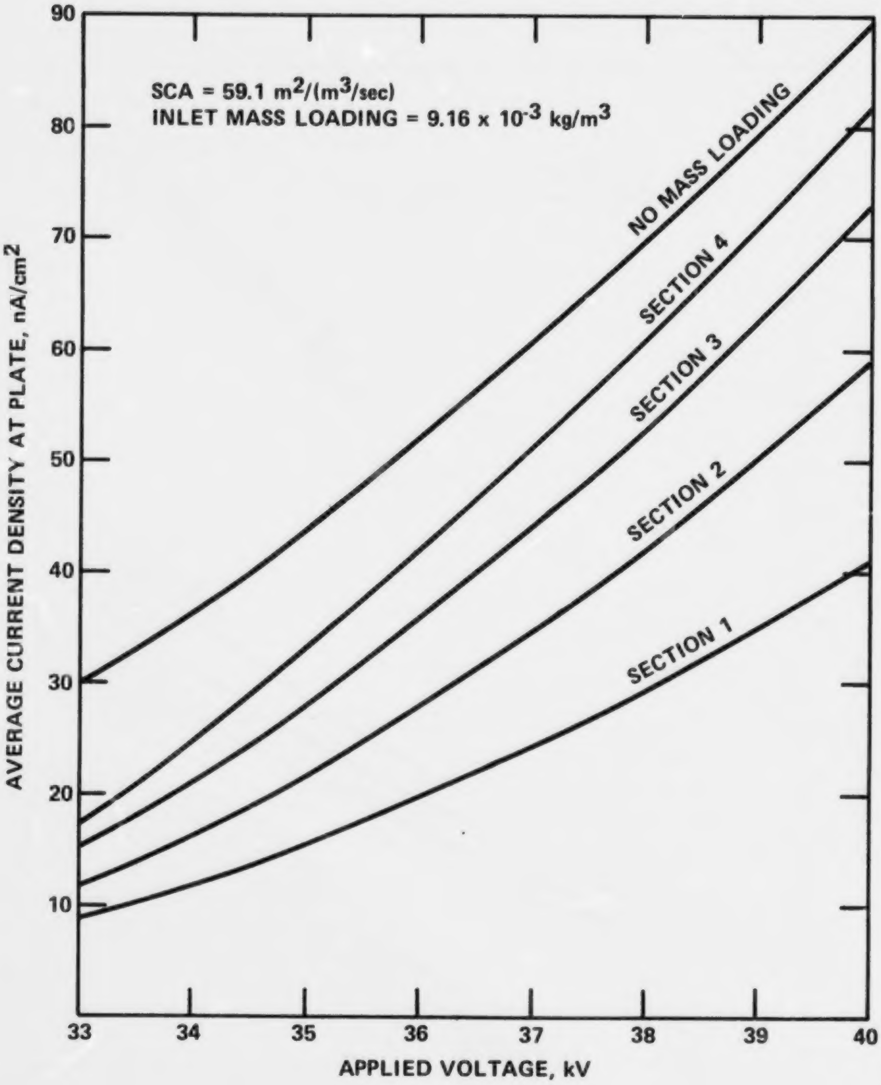


Figure 33. Theoretical voltage-current curves for a specific collection area of 59.1 $m^2/(m^3/sec)$.

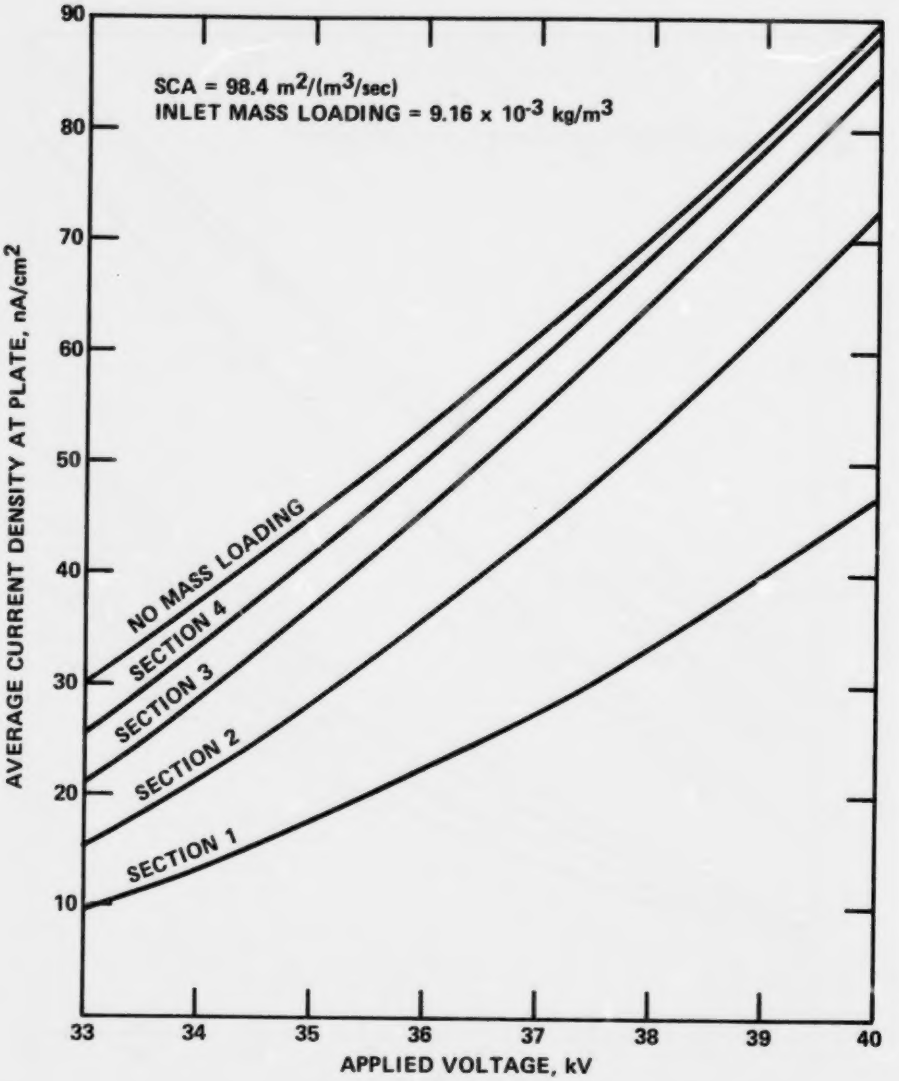


Figure 34. Theoretical voltage-current curves for a specific collection area of 98.4 m²/m³/sec).

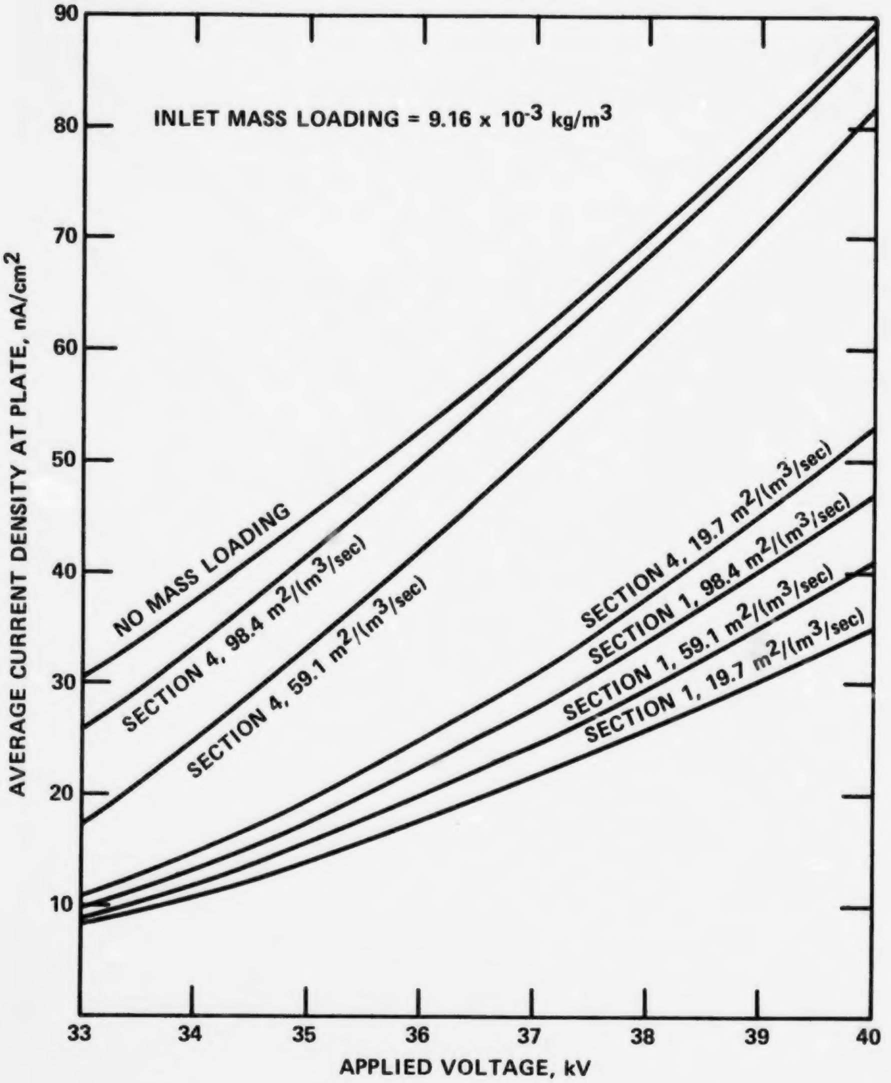


Figure 35. Comparison of theoretical voltage-current curves for different specific collection areas.

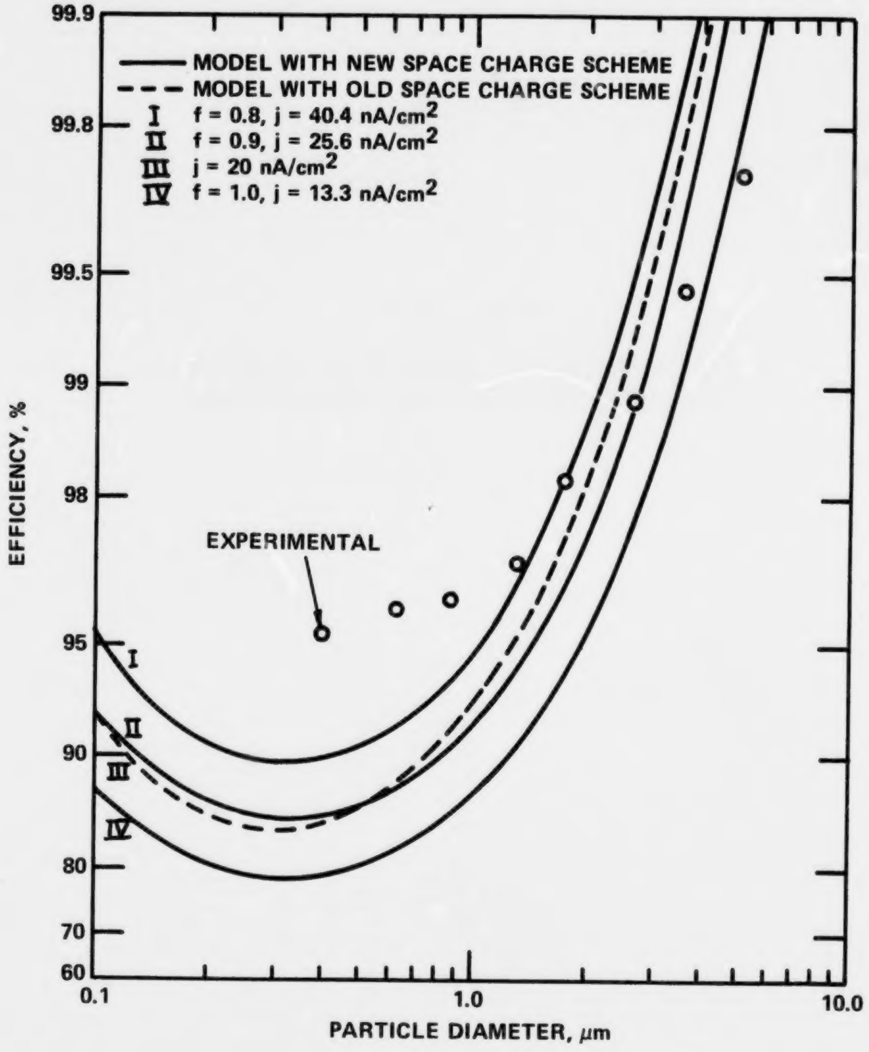


Figure 36. Comparison of model predictions using the different space charge schemes with field test data from a full-scale precipitator. Model predictions are for unadjusted, no-rap efficiencies where $\sigma_g = 0.25$ and $S = 0$.

APPENDIX B

DEFINITIONS OF VARIABLES USED IN THE MAIN PROGRAM AND SUBROUTINES

LIST OF VARIABLES, DEFINITIONS, AND UNITS FOR THE MAIN PROGRAM OF THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NWIRE - Number of wires per electrical section per gas passage in a particular electrical section

LTHICK - Thickness of the collected particulate layer in a particular increment of length (mm/min)

JPART - Current density due to particles in a particular increment of length (A/m^2)

JION - Current density due to ions in a particular increment of length (A/m^2)

LINC - Length of the increments taken in a particular linear electrical section (m)

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

VISKIP - Indicator which determines whether or not a dirty-gas voltage-current curve is calculated in each increment of length

VISAME - Indicator which determines whether or not a clean-gas voltage-current curve is calculated for each of the electrical sections or just the first electrical section

CHKSUM(K) - Fractional increase in charge from one increment to the next for the different particle sizes

DIAM(K) - Diameters of the different particle sizes (μm and m)

ONO(K) - Initial number of particles per cubic meter of gas in each particle size band (#/m^3)

DXS(K) - Total number of particles removed per cubic meter of gas in each particle size band under ideal conditions and with no empirical corrections (#/m^3)

XMV(K) - Effective migration velocities for the different particle sizes under ideal conditions and with no empirical corrections (m/sec)

PCNT(K) - Percentage or fraction by mass in the inlet particle size distribution of the different size bands (% and decimal)

RAD(K) - Radii of the different particle sizes (m)

CCF(K) - Cunningham correction factor for the different particle sizes

PRCU(L) - Cumulative percent by mass up to each particle size in the inlet particle size distribution (%)

LSECT(I) - Number of length increments in the different linear electrical sections

PS(I) - Gas pressure in the different electrical sections (atm)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

ATOTAL - Total collection plate area of the precipitator (m^2)

DD - Mass density of the particles (kg/m^3)

ETAO - Estimated or design overall mass collection efficiency (%)

DL - Inlet mass loading (grains/ft^3 and kg/m^3)

PL - Total electrical length of the precipitator (ft and m)

RHO - Resistivity of the collected particulate layer (ohm-cm and ohm-m)

NS - Number of different particle size bands in the inlet particle size distribution

ZMMDI - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMI - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NRAPD - Number of rapping puff particle size distributions to be considered

TDK - Temperature of the gas in a given electrical section (°K)

NUMSEC - Number of linear electrical sections in the precipitator

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

GFIT - Linear-correlation coefficient obtained in the lognormal fit of the inlet particle size distribution

VOL(K) - Total volume of particles per cubic meter of gas in the different size bands (m^3/m^3(gas))

XNO(K) - Number of particles per cubic meter of gas in each size band at the start of each increment ($\#/m^3$)

Q(K) - Charge on each particle size at the end of a particular increment (coul)

WS(K) - Total weight of material per cubic meter of gas removed in each size band in a particular increment (kg/m^3)

ITL(M) - Identifying label for the calculations

DW(J) - Amount of material removed per increment on a total weight basis (kg)

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

WLS(I) - Total wire length for the different linear electrical sections (ft^2)

ACS(I) - Corona wire radii for the different linear electrical sections (in.)

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in.)

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in.)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

QSAT(K) - Saturation charge for the different particle sizes (coul)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

E - Elementary charge unit (coul)

EPSO - Permittivity of free space ($coul^2/nt\text{-}m^2$)

PI - Value of the constant π

ERAVG - Average electric field used for particle charging (V/m)

BC - Boltzmann's constant (J/°K)

TEMP - Gas temperature in a particular linear electrical section (°R)

EPS - Relative dielectric constant of the particles

VAVC - Root mean square velocity of the ions (m/sec)

OLDQ(K) - Charge on the different particle sizes in the increment prior to the one under consideration (coul)

OLDXNO(K) - Number of particles per cubic meter of gas in each size band at the start of the increment prior to the one under consideration ($\#/m^3$)

RFS(I) - Roughness factor for the corona wires in the different linear electrical sections

START1(I) - Specified initial current density at which the calculation of a voltage-current curve starts in a given electrical section and the initial current density increment size (A/m^2)

START2(I) - Specified increment in current density which is used in place of START1(I) when the JI1-th point on the voltage-current curve is reached (A/m^2)

START3(I) - Specified increment in current density which is used in place of START2(I) when the JI2-th point on the voltage-current curve is reached (A/m^2)

VSTAR(I) - Estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(I) (V)

XDC(J,K) - Charge on each particle size at the end of each increment (coul)

EAVG(N) - Average electric fields for particle charging in subincremental lengths (V/m)

CHFID(N) - Average free ion densities for particle charging in subincremental lengths (#/m^3)

ECOLL(N) - Average electric fields at the plate in subincremental lengths (V/m)

ECLEAN(N) - Average electric fields at the plate for clean gas in subincremental lengths (V/m)

ENDPT(L) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

ARD50(II) - Rapping puff mass median diameters (μm)

ARSIGM(II) - Rapping puff geometric standard deviations

ASNUCK(JJ) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZNUMS(JJ) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

AZIGGY(JJ) - Normalized standard deviations of the gas velocity distribution

VCOOP(KK,LL) - Values at different grid points of the electric potential in a wire-plate geometry under conditions of no space charge (V)

TMFP - Ionic mean free path multiplied by a factor (m)

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NPRINT - Indicator which designates when to print certain sectionalized data

NSECT - Indicator which keeps track of which electrical section the calculation is in

SLNGTH - Length of a particular electrical section (m)

A - Collection plate area of a particular linear electrical section (m^2)

VO - Applied voltage in a particular linear electrical section (V)

TC - Total current in a particular linear electrical section (A)

B - Wire-to-plate spacing in a particular linear electrical section (m)

AC - Corona wire radius in a particular linear electrical section (m)

WL - Total wire length in a particular linear electrical section (m)

CL - Total current per length of corona wire in a particular linear electrical section (A/m)

CD - Average current density at the plate in a particular linear electrical section (A/m^2)

ET - Average electric field in the deposited particulate layer in a particular linear electrical section (V/m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

VGAS - Gas velocity in a particular linear electrical section (m/sec)

P - Gas pressure in a particular linear electrical section (atm)

VIS - Gas viscosity in a particular linear electrical section (kg/m-sec)

W - Total weight of particles per second passing into a particular linear electrical section (kg/sec)

XPI - Overall mass collection efficiency per increment based on the estimated or design efficiency (%)

RIOVR - Ratio of the ionic space charge density to the total space charge density

EPLT - Absolute value of the average electric field at the plate in a particular length increment (V/m)

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

XCD - Average current density at the plate in a particular length increment (nA/cm^2)

ZMD - Interpolated mass median diameter of the collected particulate layer (m)

WT - Total weight of material per cubic meter of gas removed in all particle size bands in a given length increment (kg/m^3)

I - Index which runs over the different incremental lengths in its major usage

ROVRI - Ratio of the total space charge density to the ionic space charge density

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NI - Number of subincremental lengths into which the incremental length is divided

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

NF - Number of increments taken along the length of the precipitator

NREAD - Indicator which specifies the unit number of the input device for reading data into the program

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%)

CZMDL - Fitted log-normal mass median diameter of the outlet particle size distribution under no-rap + rap conditions (μm)

CSIGMO - Fitted log-normal geometric standard deviation of the outlet particle size distribution under no-rap + rap conditions

NRUN - Indicator that specifies which set of nonideal conditions is under consideration

SNUCK - Particular value of ASNUCK(JJ)

ZIGGY - Particular value of AZIGGY(JJ)

RMMD - Particular value of ARD50(II)[μm]

RSIGMA - Particular value of ARSIGM(II)

LK - Indicator which determines whether or not the input data are printed at a certain location in the program

DV - Total volume per cubic meter of gas occupied by particles [m^3(particles)/m^3(gas)]

NN - Number of increments in the Runge-Kutta integration of equation (12)

NUMINC - Number of increments in the Simpson's Rule integration over Θ in equation (12)

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NDATA - Indicator which determines the type of data set that is to be read into the program

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

JI1 - Indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve

JI2 - Indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

FPATH - Factor which scales the ion mean free path

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

NDSET - Counter which keeps track of the number of the particular set of nonideal conditions which is under consideration

D50 - Same as ZMMDI (μm)

SIGMAP - Same as SIGMI

SCHARG - Saturation charge number from the field charging equation

CHRFID - Average free ion density for particle charging ($\#/m^3$)

TIMEI - Initial value of time for particle charging (sec)

TIMEF - Final value of time for particle charging (sec)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (12)

FACTRE - Value of the quantity $[\pi\tilde{v}a^2/2]$ found in equation (12) $[m^3/sec]$

RSIZE - Radius of a particular particle (m)

CNUMBR - Charge number of a particular particle at time TIMEF

J - Index which runs over different particle size bands

II - Index which runs over subincremental lengths

ITER - Counter which keeps track of the number of iterations which is limited by NITER

OLDQF(K) - Value of field charge on the different particle sizes at the end of a given increment or subincrement (coul)

OLDQT(K) - Value of diffusion charge on the different particle sizes at the end of a given increment or subincrement (coul)

SOLDQF(K) - Value of field charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

SOLDQT(K) - Value of diffusion charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $[\text{coul}^2/\text{nt-m}^2]$

KA - Index which runs over the different linear electrical sections

ZWT - Total weight of material per cubic meter of gas removed up to a given increment (kg/m^3)

RATIO - Value of the quantity [(K-1)/(K+2)] found in the particle charging equations

G - Value of the quantity [K+2] found in the particle charging equations

INDEX - Indicator which keeps track of how many increments the calculation is into a particular linear electrical section

NCOOP - Indicator which allows certain calculations to be made only at the start of a new linear electrical section

SX - Wire-to-plate spacing in a particular linear electrical section (m)

RF - Roughness factor for the discharge wires in a particular linear electrical section

START - Particular value of START1(I) $[A/m^2]$

DSTART - Particular value of START2(I) $[A/m^2]$

CSTART - Particular value of START3(I) $[A/m^2]$

VSTART - Particular value of VSTAR(I) [V]

ZMFP - Ionic mean free path (m)

VAVG - Root mean square velocity of the ions (cm/sec)

VC - Value of the quantity $[e^2/kT]$ found in the charging equations (coul/V)

FACTRC - Value of the quantity $[\pi\tilde{v}/2]$ found in the charging equations (m/sec)

COEFFC - Value of the quantity $[e\pi b]$ found in the charging equations $(\text{coul-m}^2/\text{V-sec})$

TINC - Time interval for the gas to travel one increment (sec)

DTINC - Time interval for the gas to travel one subincrement (sec)

L - Index which runs over the different particle size bands

R - Value of the quantity $[eE_0/kT(K+2)]$ found in equation (12) $[m^{-1}]$

RR - Value of the quantity $[eE_0/kT]$ found in equation (12) $[m^{-1}]$

RG - Same as RR

VW - Operating applied voltage corresponding to a specified current density (V)

UEQ - Effective charge carrier mobility $(m^2/\text{V-sec})$

NEC - Indicator which determines whether or not the average current density, average electric field, and average electric field at the plate are to be calculated in the subincremental lengths

AEPLT - Average electric field at the plate in a particular increment (V/m)

ACDNTY - Average current density at the plate in a particular increment (A/m^2)

NZ - Index which runs over subincremental lengths

CDCLN - Average current density at the plate when the gas is clean (A/m^2)

USUM - Sum of effective charge carrier mobilities over the subincremental lengths in a particular incremental length (m^2/V-sec)

WSSUM - Total weight of material per cubic meter of gas removed in a particular size band in a particular subincrement (kg/m^3)

RHOSUM - Sum of the ratio of the ionic space charge to the total space charge over the subincremental lengths in a particular incremental length

SW - Cumulative sum of estimated amount of material removed per second in successive length increments (kg/sec)

OROVRI - Ratio of total charge density to ionic charge density in increment prior to the one the calculation is in

XS - Computed value of the exponential argument in the Deutsch equation for the estimated or design overall mass collection efficiency

ETAPF - Overall mass collection fraction per increment based on the estimated or design efficiency

FID - Average free ion density (#/m^3)

AVGFID - Average reduced free ion density for particle charging (#/cm^3)

PROT - Total charge density due to particles that remain after passing through a given increment (coul/m^3)

SERAVG - Average electric field in a particular increment (V/m)

XIPC - Initial value of charge number on a given particle size at the start of a new increment

H - Increment size for the Runge-Kutta integration of equation (12) [sec]

DCONST - Value of the quantity $[(K-1)a^3/(K+2)]$ found in equation (12) [m^3]

CONST - Value of the quantity $[2(K-1)a^3E_0/(K+2)]$ found in equation (12) [$V-m^2$]

S - Value of the quantity [3a] found in equation (12)[m]

ECONST - Value of the quantity $[3eE_0a/kT(K+2)]$ found in equation (12)

FCONST - Value of the quantity $[(K-1)eE_0a^3/kT(K+2)]$ found in equation (12) [m^2]

COEFF - Value of the quantity $[bqs/4\varepsilon_0]$ found in equation (12) [m^3/sec]

CTIME - Time at the end of a given increment (sec)

EMV(K) - Unadjusted, ideal migration velocities for the different particle sizes in a given increment (m/sec)

X - Exponent used in the Deutsch equation to determine the unadjusted, ideal collection fractions for the different particle sizes in a given increment

EFF - Unadjusted, ideal collection fraction for a given particle size band in a given increment

DXNO - Number of particles per cubic meter of gas removed from a given particle size band in a given increment ($\#/m^3$)

DNSION - Ion density in the absence of particles ($\#/m^3$)

DELTNP - Number density of charges transferred from ions to particles in a given subincremental length ($\#/m^3$)

SUMMOB - Weighted summation of particle mobilities ($m^2/V-sec/m^3$)

PNUM - Total number of particles per unit volume of gas entering a given subincremental length ($\#/m^3$)

RHOP - Total average particulate charge density in a given subincremental length ($coul/m^3$)

TCHRG - Average particle charge density for a given particle size in a given subincremental length ($coul/m^3$)

PMOB - Weighted particulate mobility in a given subincremental length (m^2/V-sec)

TDNSP - Total average particulate charge number density in a given subincremental length (#/m^3)

RDNSI - Average reduced ion density in a given subincremental length (#/m^3)

SUMCD - Sum of the average current densities at the plate from the different increments in a particular linear electrical section (A/m^2)

SUMVO - Sum of the applied voltages from the different increments in a particular linear electrical section (V)

SKIP - Electric field at the plate in the increment prior to the one the calculation is in (V/m)

SIGMA - Difference between the ratio of the total space charge density to the ionic space charge density in the (I+1)-th and I-th increments

VERGE - Initial estimate of the space charge density at the corona wire to start the calculation of the electric field at the plate (coul/m^3)

CVERGE - Converged value of the space charge density at the wire in calculating the electric field at the plate (coul/m^3)

ZTM - Cumulative sum of the weight of material per cubic meter of gas collected up to a given particle size in a given increment (kg/m^3)

CZA - Ratio of the partial sum of the weight of dust removed per cubic meter of gas up the K-th particle size in a given increment to the total weight of dust removed per cubic meter of gas in a given increment

CZB - Ratio of the partial sum of the weight of dust removed per cubic meter of gas up to the (K-1)-th particle size in a given increment to the total weight of dust removed per cubic meter of gas in a given increment

TL1 - Difference between CZA and CZB for use in interpolating to find the mass median diameter of the collected dust

TL2 - Difference between 0.50 and CZB for use in interpolating to find the mass median diameter of the collected dust

KJ - Index which runs simultaneously with the index which runs over the different particle sizes and keeps track of the (K-1)-th particle size

ETC - Ideal, unadjusted overall mass collection efficiency for the entire precipitator (%)

DIFF - Difference between the calculated ideal, unadjusted overall mass collection efficiency and the estimated value

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTINP USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

LK - Indicator which determines whether or not the input data are printed at a certain location in the program

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

NDSET - Counter which keeps track of the number of the particular set of nonideal conditions which is under consideration

DL - Inlet mass loading (kg/m^3)

DLB - Inlet mass loading (grains/ft^3)

PL - Total electrical length of the precipitator (m)

PLB - Total electrical length of the precipitator (ft)

RHO - Resistivity of the collected particulate layer (ohm-m)

RHOCGS - Resistivity of the collected particulate layer (ohm-cm)

NCARD - Counter which keeps track of the number of each successive imput data card

NENDPT - Number of particle diameters in the inlet cumulative percent by mass distribution

NDATA - Indicator which determines the type of data set that is to be read into the program

ITL(M) - Identifying label for the calculations

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NITER - Indicator which determines the maximum number of iterations over a loop that converges on overall mass efficiency or the number of iterations that will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NRAPD - Number of rapping puff particle size distributions to be considered

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NN - Number of increments in the Runge-Kutta integration of equation (12)

NUMINC - Number of increments in the Simpson's Rule integration over Θ in equation (12)

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

JI1 - Indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve

JI2 - Indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve

VISKIP - Indicator which determines whether or not a dirty-gas voltage-current curve is calculated in each increment of length

VISAME - Indicator which determines whether or not a clean-gas voltage-current curve is calculated for each of the electrical sections or just the first electrical section

ETAO - Estimated or design overall mass collection efficiency (%)

DD - Mass density of the particles (kg/m^3)

EPS - Relative dielectric constant of the particles

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

US - Ion mobility at standard temperature and pressure (reduced ion mobility)

FPATH - Factor which scales the ion mean free path

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

ARD50(II) - Rapping puff mass median diameters (μm)

ARSIGM(II) - Rapping puff geometric standard deviations

ASNUCK(JJ) - Fractions of gas sneakage and/or particle reentrainment without rapping

AZIGGY(JJ) - Normalized standard deviations of the gas velocity distribution

AZNUMS(JJ) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

NDCARD - Indicator which determines how the arrays ENDPT(L) and PRCU(L) should be printed

ENDPT(L) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

PRCU(L) - Cumulative percent by mass up to each particle size in the inlet particle size distribution (%)

NUMSEC - Number of linear electrical sections in the precipitator

LSECT(I) - Number of length increments in the different linear electrical sections

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

WLS(I) - Total wire length for the different linear electrical sections (ft^2)

ACS(I) - Corona wire radii for the different linear electrical sections (in.)

BS(I) - Wire-to-plate spacing for the different linear electrical sections (in.)

NWS(I) - Number of wires per electrical section per gas passage for the different linear electrical sections

SYS(I) - One-half the wire-to-wire spacing for the different linear electrical sections (in.)

VGS(I) - Gas volume flow rate for the different linear electrical sections (ft^3/min)

VGASS(I) - Gas velocity for the different linear electrical sections (ft/sec)

TEMPS(I) - Gas temperature for the different linear electrical sections (°F)

PS(I) - Gas pressure in the different electrical sections (atm)

VISS(I) - Gas viscosity for the different linear electrical sections (kg/m-sec)

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

RFS(I) - Roughness factor for the corona wires in the different linear electrical sections

START1(I) - Specified initial current density at which the calculation of a voltage-current curve starts in a given electrical section and the initial current density increment size (A/m^2)

START2(I) - Specified increment in current density which is used in place of START1(I) when the JI1-th point on the voltage-current curve is reached (A/m^2)

START3(I) - Specified increment in current density which is used in place of START2(I) when the JI2-th point on the voltage-current curve is reached (A/m^2)

VSTAR(I) - Estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(I) (V)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE SPCHG1 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

I - Index which runs over the incremental lengths

SW - Cumulative sum of estimated amount of material removed per second in successive length increments (kg/sec)

ROVRI - Ratio of the total space charge density to the ionic space charge density

OROVRI - Ratio of total charge density to ionic charge density in increment prior to the one the calculation is in

ETAO - Estimated overall mass collection efficiency (%)

XS - Computed value of the exponential argument in the Deutsch equation for the estimated overall mass collection efficiency

LINC - Length of the increments taken in a particular linear electrical section (m)

PL - Total electrical length of the precipitator (m)

ETAPF - Overall mass collection fraction per increment based on the estimated efficiency

W - Total weight of particles per second passing into a particular linear electrical section (kg/sec)

DW(J) - Amount of material removed per increment on a total weight basis (kg)

CD - Average current density at the plate in a particular linear electrical section (A/m^2)

E - Elementary charge unit (coul)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

ERAVG - Average electric field used for particle charging (V/m)

FID - Average free ion density (#/m^3)

SUM - Total particulate charge density in a given increment based on saturation charges (coul/m^3)

NS - Number of different particle size bands in the inlet particle size distribution

L - Index which runs over the different particle size bands

QSAT(L) - Saturation charge for the different particle sizes (coul)

XNO(L) - Number of particles per cubic meter of gas in each size band at the start of each increment (#/m^3)

LSECT(I) - Number of length increments in the different linear electrical sections

NSECT - Indicator which keeps track of which electrical section the calculation is in

TC - Total current in a particular linear electrical section (A)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

ZC - Ratio of the particulate charge density to the ionic charge density (ratio of 200 times the particulate current to the total current)

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

AVGFID - Average reduced free ion density for particle charging (#/cm^3)

XCD - Average current density at the plate in a particular length increment (nA/cm^2)

UEQ - Effective charge carrier mobility (m^2/V-sec)

XPI - Overall mass collection efficiency per increment based on the estimated efficiency (%)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE SPCHG2 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

I - Index which runs over the incremental lengths

ETAO - Design overall mass collection efficiency (%)

XS - Computed value of the exponential argument in the Deutsch equation for the design overall mass collection efficiency

LINC - Length of the increments taken in a particular linear electrical section (m)

PL - Total electrical length of the precipitator (m)

ETAPF - Overall mass collection fraction per increment based on the design efficiency

DELTNP - Number density of charges transferred from ions to particles in a given subincremental length ($\#/m^3$)

SUMMOB - Weighted summation of particle mobilities ($m^2/V\text{-sec}/m^3$)

PNUM - Total number of particles per unit volume of gas entering a given subincremental length ($\#/m^3$)

RHOP - Total average particulate charge density in a given subincremental length ($coul/m^3$)

J - Index which runs over the different particle size bands

XNO(J) - Number of particles per cubic meter of gas in each size band at the start of each increment ($\#/m^3$)

XDC(I,J) - Charge on each particle size at the end of each increment (coul)

TCHRG - Average particle charge density for a given particle size in a given subincremental length ($coul/m^3$)

CCF(J) - Cunningham correction factor for the different particle sizes

VIS - Gas viscosity in a particular linear electrical section (kg/m-sec)

RAD(J) - Radii of the different particle sizes (m)

DIFF - Difference between the charge on a given particle size in the (I+1)-th and I-th increments (coul)

II - Index which runs over the subincremental lengths

Q(J) - Charge on each particle size at the end of a particular increment (coul)

OLDQ(J) - Charge on the different particle sizes in the increment prior to the one under consideration (coul)

PMOB - Weighted particulate mobility in a given subincremental length (m^2/V-sec)

TDNSP - Total average particulate charge number density in a given subincremental length (#/m^3)

CHFID(II) - Average free ion densities for particle charging in subincremental lengths (#/m^3)

DNSION - Ion density in the absence of particles (#/m^3)

RDNSI - Average reduced ion density in a given subincremental length (#/m^3)

PIR - Ratio of the total charge density which can be accepted by particles in a given subincrement to the available free ion density

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

AVGFID - Average reduced free ion density for particle charging (#/cm^3)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

E - Elementary charge unit (coul)

UEQ - Effective charge carrier mobility (m^2/V-sec)

RIOVR - Ratio of the ionic space charge density to the total space charge density

XPI - Overall mass collection efficiency per increment based on the design efficiency (%)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CMAN USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

NX1 - Number of grid intervals in the x-direction for the numerical calculations of electrical conditions

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

NY1 - Number of grid intervals in the y-direction for the numerical calculations of electrical conditions

SX - Wire-to-plate spacing in a particular linear electrical section (m)

AX - Interval size in the x-direction (m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

AY - Interval size in the y-direction (m)

I - Index which runs over grid points in the x-direction

J - Index which runs over grid points in the y-direction

X - Value of x used in equation (26) [m]

Y - Value of y used in equation (26) [m]

VW - Electrical potential at the wire (V)

VCOOP(I,J) - Array containing the values of electric potential given equation (26) at the different grid points (V)

NWIRE - Number of wires per electrical section per gas passage in a particular electrical section

M - Series sum in equation (26) is taken from -M to M

NUM - Sum in the numerator of equation (26)

DENOM - Sum in the denominator of equation (26)

PI - Value of the constant π

E1 - Arguments for the hyperbolic cosine functions in the numerator of equation (26)

F1 - Arguments for the cosine functions in the numerator of equation (26)

G1 - Arguments for the hyperbolic cosine functions in the denominator of equation (26)

H1 - Arguments for the cosine functions in the denominator of equation (26)

E2 - Hyperbolic cosine functions in the denominator of equation (26)

F2 - Cosine functions in the denominator of equation (26)

G2 - Hyperbolic cosine functions in the denominator of equation (26)

H2 - Cosine functions in the denominator of equation (26)

TT - Argument for the logarithmic function in the numerator of equation (26)

TB - Argument for the logarithmic function in the denominator of equation (26)

F - Logarithmic function in the numerator of equation (26)

G - Logarithmic function in the denominator of equation (26)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE EFLD1 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

VO - Applied voltage (negative value used in calculations) [V]

PI - Value of the constant π

EPSO - Permittivity of free space ($\text{coul}^2/\text{nt-m}^2$)

AC - Radius of the corona wires (m)

RO - Radius of the corona wires (m)

ROC - Radius of the corona wires (cm)

RF - Roughness factor for the corona wires

TDK - Temperature of the gas stream (°K)

P - Pressure in the gas stream (atm)

RELD - Relative air density [$\delta = (T_0/T)(P/P_0)$]

EORO - Product of the corona starting electric field and the wire radius

CD - Average current density at the plate (A/m^2)

UEQ - Effective charge carrier mobility ($m^2/\text{V-sec}$)

VERGE - Initial estimate of the space charge density at the corona wire to start the calculation of the electric field at the plate (coul/m^3)

QZERO - Space charge density at the corona wire (coul/m^3)

I - Index which runs over grid points in the x-direction

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

J - Index which runs over grid points in the y-direction

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

MOBILT(I,J) - Array containing the values of effective charge carrier mobility at the different grid points (m^2/V-sec)

MAXJ - Upper limit that the calculated average current density at the plate cannot exceed (A/m^2)

MINJ - Lower limit that the calculated average current density at the plate cannot fall below (A/m^2)

NX1 - Number of grid intervals in the x-direction for the numerical calculations of electrical conditions

NY1 - Number of grid intervals in the y-direction for the numerical calculations of electrical conditions

SX - Wire-to-plate spacing in a particular linear electrical section (m)

AX - Interval size in the x-direction (m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

AY - Interval size in the y-direction (m)

AXS - Value of the quantity $[a_x{}^2]$ (m^2)

AYS - Value of the quantity $[a_y{}^2]$ (m^2)

ASP - Value of the quantity $[(a_x{}^2+a_y{}^2)/\varepsilon_0]$ (m^4-nt/coul^2)

ASS - Value of the quantity $[1/2(a_x{}^2+a_y{}^2)]$ (m^{-2})

Z - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the average current density at the plate

VCOOP(I,J) - Array containing the values of electric potential given equation (26) at the different grid points (V)

V(I,J) - Array containing the value of the electric potential at each point in the grid during an iteration (V)

IZ - Same as Z

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

LL - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the electric potential at each point in the grid

RHO(I,J) - Array containing the value of the space charge density at each point in the grid during an iteration (coul/m^3)

EX(I,J) - Array containing the value of the component of the electric field intensity perpendicular to the plates at each point in the grid during an iteration (V/m)

EY(I,J) - Array containing the value of the component of the electric field intensity parallel to the plates at each point in the grid during an iteration (V/m)

Q1 - Value of the quantity $[2b_{i,1}]$ along the line AD where $b_{i,j}$ is the effective charge carrier mobility which is a function of position (m^2/V-sec)

Q2 - Value of the quantity $[2b_{i,1}a_x]$ along the line AD (m^3/V-sec)

Q3 - Value of the quantity $[2b_{i,1}a_y]$ along the line AD (m^3/V-sec)

Q4 - Value of the quantity $[2b_{i,1}a_x a_y]$ along the line AD (m^4/V-sec)

Q5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,1}a_y - a_y b_{i-1,1})]$ along the line AD (coul^2/nt-sec)

Q6 - Value of the quantity $[\varepsilon_0{}^2 E_x{}^2(2b_{i,1}a_y - a_y b_{i-1,1})^2]$ along the line AD (coul^4/nt^2-sec^2)

Q7 - Value of the quantity $[4b_{i,1}^2 a_x a_y{}^2 \varepsilon_0 E_x \rho_{i-1,1}]$ along the line AD where $\rho_{i,j}$ is the space charge density at the different grid points (coul^2-m^2/V^2-sec^2)

Q8 - Value of the quantity $[-\sqrt{Q6+Q7}]$ along the line AD (coul-m/V-sec)

P1 - Value of the quantity $[2b_{i,j}]$ along the line AB (m^2/V-sec)

P2 - Value of the quantity $[2b_{i,j}a_x]$ along the line AB (m^3/V-sec)

P3 - Value of the quantity $[2b_{1,j}a_y]$ along the line AB (m^3/V-sec)

P4 - Value of the quantity $[2b_{1,j}a_x a_y]$ along the line AB (m^4/V-sec)

P5 - Value of the quantity $[-\varepsilon_0 E_y(2b_{1,j}a_x - a_x b_{1,j-1})]$ along the line AB ($coul^2$/nt-sec)

P6 - Value of the quantity $[\varepsilon_0^2 E_y^2(2b_{1,j}a_x - a_x b_{1,j-1})^2]$ along the line AB ($coul^4/nt^2$-sec^2)

P7 - Value of the quantity $[4b^2_{1,j}a_x^2 a_y \varepsilon_0 E_y \rho_{1,j-1}]$ along the line AB ($coul^2$-m^2/V^2-sec^2)

P8 - Value of the quantity $[-\sqrt{P6+P7}]$ along the line AB (coul-m/V-sec)

R1 - Value of the quantity $[2b_{i,NY}]$ along the line BC (m^2/V-sec)

R2 - Value of the quantity $[2b_{i,NY}a_x]$ along the line BC (m^3/V-sec)

R3 - Value of the quantity $[2b_{i,NY}a_y]$ along the line BC (m^3/V-sec)

R4 - Value of the quantity $[2b_{i,NY}a_x a_y]$ along the line BC (m^4/V-sec)

R5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,NY}a_y - a_y b_{i-1,NY})]$ along the line BC ($coul^2$/nt-sec)

R6 - Value of the quantity $[\varepsilon_0^2 E_x^2(2b_{i,NY}a_y - a_y b_{i-1,NY})]$ along the line BC ($coul^4/nt^2$-sec^2)

R7 - Value of the quantity $[4b^2_{i,NY}a_x a_y^2 \varepsilon_0 E_x \rho_{i-1,NY}]$ along the line BC ($coul^2$-m^2/V^2-sec^2)

R8 - Value of the quantity $[-\sqrt{R6+R7}]$ along the line BC (coul-m/V-sec)

D1 - Value of the quantity $[2b_{i,j}]$ for interior points in the grid (m^2/V-sec)

D2 - Value of the quantity $[2a_x b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D3 - Value of the quantity $[2a_y b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D4 - Value of the quantity $[2a_x a_y b_{i,j}]$ for interior points in the grid (m^4/V-sec)

D5 - Value of the quantity $[-\varepsilon_0(E_x(2a_y b_{i,j}-a_y b_{i-1,j}) + E_y(2a_x b_{i,j}-a_x b_{i,j-1}))]$ for interior points in the grid ($coul^2$/nt-sec)

D6 - Value of the quantity [D5·D5] ($coul^4/nt^2-sec^2$)

D7 - Value of the quantity $[4b_{i,j}^2 a_x a_y \varepsilon_0(a_y E_x \rho_{i-1,j} + a_x E_y \rho_{i,j-1})]$ for interior points in the grid ($coul^2$-m^2/V^2-sec^2)

D8 - Value of the quantity $[-\sqrt{D6+D7}]$ for interior points in the grid (coul-m/V-sec)

OLDV(I,J) - Array containing the value of the electric potential at each point in the grid during the previous iteration (V)

OLDRO(I,J) - Array containing the value of the space charge density at each point in the grid during the previous iteration (coul/m^3)

CDNSTY(I,J) - Array containing the value of current density at each point in the grid (A/m^2)

ACDNTY - Average current density at the plate (A/m^2)

EPLT - Sum of the values of the electric field intensity at the plate (V/m)

AEPLT - Average electric field at the plate (V/m)

CVERGE - Converged value of the space charge density at the wire in calculating the electric field at the plate (coul/m^3)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE EFLD2 USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

IVCK - Indicator which terminates the calculation of points on the voltage-current whenever the specified applied voltage is reached and interpolated upon

VO - Specified operating applied voltage (V)

VSTART - Particular value of VSTAR(I) [V]

VW - Operating applied voltage corresponding to a specified current density (V)

AC - Radius of the corona wires (m)

RO - Radius of the corona wires (m)

TDK - Temperature of the gas stream (°K)

P - Pressure of the gas stream (atm)

RELD - Relative air density $[\delta = (T_0/T)(P/P_0)]$

ROC - Radius of the corona wires (cm)

RF - Roughness factor for the corona wires

EORO - Product of the corona starting electric field and the wire radius (V)

I - Index which runs over grid points in the x-direction

NX - Number of grid points in the x-direction for the numerical calculations of electrical conditions

J - Index which runs over grid points in the y-direction

NY - Number of grid points in the y-direction for the numerical calculations of electrical conditions

UEQ - Effective charge carrier mobility (m^2/V-sec)

MOBILT(I,J) - Array containing the values of effective charge carrier mobility at the different grid points (m^2/V-sec)

PI - Value of the constant π

EPSO - Permittivity of free space ($coul^2/nt-m^2$)

START - Particular value of START1(I) [A/m^2]

SSTART - Initial value of START which is saved (A/m^2)

MINJ - Lower limit that the calculated average current density at the plate cannot fall below (A/m^2)

MAXS - Particular value of current density on the voltage-current curve (A/m^2)

NX1 - Number of grid intervals in the x-direction for the numerical calculations of electrical conditions

NY1 - Number of grid intervals in the y-direction for the numerical calculations of electrical conditions

SX - Wire-to-plate spacing in a particular linear electrical section (m)

AX - Interval size in the x-direction (m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section

AY - Interval size in the y-direction (m)

AXS - Value of the quantity [${a_x}^2$] (m^2)

AYS - Value of the quantity [${a_y}^2$] (m^2)

ASP - Value of the quantity [$({a_x}^2+{a_y}^2)/\varepsilon_0$] ($m^4$-nt/$coul^2$)

ASS - Value of the quantity [$1/2({a_x}^2+{a_y}^2)$](m^{-2})

IFINAL - Indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points

II - Index which runs over the different current densities to be used on the voltage-current curve

JI1 - Indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after JI1-1 points are determined on the curve

DSTART - Particular value of START2(I) [A/m^2]

JI2 - Indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve

CSTART - Particular value of START3(I) [A/m^2]

MAXJ - Upper limit that the calculated average current density at the plate cannot exceed (A/m^2)

QZERO - Space charge density at the corona wire (coul/m^3)

[illegible] - Number of wires per electrical section per gas passage in a particular electrical section

Z - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the average current density at the plate

VCOOP(I,J) - Array containing the values of electric potential given equation (26) at the different grid points (V)

V(I,J) - Array containing the value of the electric potential at each point in the grid during an iteration (V)

IZ - Same as Z

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

LL - Counter which keeps track of the number of times the calculation iterates due to lack of convergence in the electric potential at each point in the grid

RHO(I,J) - Array containing the value of the space charge density at each point in the grid during an iteration (coul/m^3)

EX(I,J) - Array containing the value of the component of the electric field intensity perpendicular to the plates at each point in the grid during an iteration (V/m)

EY(I,J) - Array containing the value of the component of the electric field intensity parallel to the plates at each point in the grid during an iteration (V/m)

Q1 - Value of the quantity $[2b_{i,1}]$ along the line AD where $b_{i,j}$ is the effective charge carrier mobility which is a function of position $(m^2/V\text{-sec})$

Q2 - Value of the quantity $[2b_{i,1}a_x]$ along the line AD $(m^2/V\text{-sec})$

Q3 - Value of the quantity $[2b_{i,1}a_y]$ along the line AD $(m^3/V\text{-sec})$

Q4 - Value of the quantity $[2b_{i,1}a_xa_y]$ along the line AD $(m^4/V\text{-sec})$

Q5 - Value of the quantity $[-\varepsilon_0E_x(2b_{i,1}a_y-a_yb_{i-1,1})]$ along the line AD $(coul^2/nt\text{-sec})$

Q6 - Value of the quantity $[\varepsilon_0{}^2E_x{}^2(2b_{i,1}a_y-a_yb_{i-1,1})^2]$ along the line AD $(coul^4/nt^2\text{-sec}^2)$

Q7 - Value of the quantity $[4b_{i,1}^2a_xa_y{}^2\varepsilon_0E_x\rho_{i-1,1}]$ along the line AD where $\rho_{i,j}$ is the space charge density at the different grid points $(coul^2\text{-}m^2/V^2\text{-sec}^2)$

Q8 - Value of the quantity $[-\sqrt{Q6+Q7}]$ along the line AD $(coul\text{-}m/V\text{-sec})$

P1 - Value of the quantity $[2b_{1,j}]$ along the line AB $(m^2/V\text{-sec})$

P2 - Value of the quantity $[2b_{1,j}a_x]$ along the line AB $(m^3/V\text{-sec})$

P3 - Value of the quantity $[2b_{1,j}a_y]$ along the line AB $(m^3/V\text{-sec})$

P4 - Value of the quantity $[2b_{1,j}a_xa_y]$ along the line AB $(m^4/V\text{-sec})$

P5 - Value of the quantity $[-\varepsilon_0E_y(2b_{1,j}a_x-a_xb_{1,j-1})]$ along the line AB $(coul^2/nt\text{-sec})$

P6 - Value of the quantity $[\varepsilon_0{}^2E_y{}^2(2b_{1,j}a_x-a_xb_{1,j-1})^2]$ along the line AB $(coul^4/nt^2\text{-sec}^2)$

P7 - Value of the quantity $[4b^2_{1,j}a_x{}^2a_y\varepsilon_0E_y\rho_{1,j-1}]$ along the line AB $(coul^2\text{-}m^2/V^2\text{-sec}^2)$

P8 - Value of the quantity $[-\sqrt{P6+P7}]$ along the line AB (coul-m/V-sec)

R1 - Value of the quantity $[2b_{i,NY}]$ along the line BC (m^2/V-sec)

R2 - Value of the quantity $[2b_{i,NY}a_x]$ along the line BC (m^3/V-sec)

R3 - Value of the quantity $[2b_{i,NY}a_y]$ along the line BC (m^3/V-sec)

R4 - Value of the quantity $[2b_{i,NY}a_x a_y]$ along the line BC (m^4/V-sec)

R5 - Value of the quantity $[-\varepsilon_0 E_x(2b_{i,NY}a_y - a_y b_{i-1,NY}]$ along the line BC ($coul^2$/nt-sec)

R6 - Value of the quantity $[\varepsilon_0{}^2 E_x^2(2b_{i,NY}a_y - a_y b_{i-1,NY}]$ along the line BC ($coul^4/nt^2$-sec^2)

R7 - Value of the quantity $[4b_{i,NY}^2 a_x a_y^2 \varepsilon_0 E_x \rho_{i-1,NY}]$ along the line BC ($coul^2$-m^2/V^2-sec^2)

R8 - Value of the quantity $[-\sqrt{R6+R7}]$ along the line BC (coul-m/V-sec)

D1 - Value of the quantity $[2b_{i,j}]$ for interior points in the grid (m^2/V-sec)

D2 - Value of the quantity $[2a_x b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D3 - Value of the quantity $[2a_y b_{i,j}]$ for interior points in the grid (m^3/V-sec)

D4 - Value of the quantity $[2a_x a_y b_{i,j}]$ for interior points in the grid (m^4/V-sec)

D5 - Value of the quantity $[-\varepsilon_0(E_x(2a_y b_{i,j} - a_y b_{i-1,j}) + E_y(2a_x b_{i,j} - a_x b_{i,j-1}))]$ for interior points in the grid ($coul^2$/nt-sec)

D6 - Value of the quantity $[D5 \cdot D5]$ ($coul^4/nt^2$-sec^2)

D7 - Value of the quantity $[4b_{i,j}^2 a_x a_y \varepsilon_0(a_y E_x \rho_{i-1,j} + a_x E_y \rho_{i,j-1})]$ for interior points in the grid ($coul^2$-m^2/V^2-sec^2)

D8 - Value of the quantity $[-\sqrt{D6+D7}]$ for interior points in the grid (coul-m/V-sec)

OLDV(I,J) - Array containing the value of the electric potential at each point in the grid during the previous iteration (V)

OLDRO(I,J) - Array containing the value of the space charge density at each point in the grid during the previous iteration (coul/m^3)

CDNSTY(I,J) - Array containing the value of current density at each point in the grid (A/m^2)

ACDNTY - Average current density at the plate (A/m^2)

TEST - Absolute value of the difference between the calculated average current density at the plate and the specified value (A/m^2)

TEST1 - One percent of the calculated average current density at the plate (A/m^2)

EPLT - Sum of the values of the electric field intensity at the plate (V/m)

AEPLT - Average electric field at the plate (V/m)

EBD - Electrical breakdown strength of the gas near the collection electrode or the collected particulate layer (V/m)

OLDVW - The value of applied voltage at the point prior to the one under consideration (V)

OLDCD - The value of average current density at the plate at the point prior to the one under consideration (A/m^2)

NEC - Indicator which determines whether or not the average current density, average electric field, and average electric field at the plate are to be calculated in the subincremental lengths

K - Index which sequences the grid strips in the basic area for which the calculations are performed

RSUM - Average charge number density in a particular grid strip (#/m^3)

ESUM - Average electric field intensity in a particular grid strip (V/m)

EAVGS(K) - Array containing the average electric field intensities in the different grid strips in the basic area for which the calculations are performed (V/m)

CHFIDS(K) - Array containing the average charge number densities in the different grid strips in the basic area for which the calculations are performed (#/m^3)

NYY - Index which renumbers the grid strips so that by symmetry the area covered by the half-wire spacing which was not considered in the calculations can be taken into account

EAVG(L) - Array containing the average electric field intensities in the different grid strips which cover an area between successive wires (V/m)

CHFID(L) - Array containing the average charge number densities in the different grid strips which cover an area between successive wires (#/m^3)

L - Index which runs over and numbers the first (NY-1) grid strips in a given wire-to-wire spacing

KK - Index which runs over the different grid strips in the basic area for which the calculations are performed

M1 - Number of the first grid strip in the last (NY-1) grid strips in a given wire-to-wire spacing

M2 - Number of the last grid strip in a given wire-to-wire spacing

M - Index which runs over and numbers the last (NY-1) grid strips in a given wire-to-wire spacing

LL - Index which sequences the grid strips in the basic area for which the calculations are performed

NN - Index which runs over points in the y-direction

ECOLLS(LL) - Array containing the average electric field intensity at the plate in the different grid strips in the basic area for which the calculations are performed (V/m)

L1 - Index which renumbers the grid strips so that by symmetry the area covered by the half-wire spacing which was not considered in the calculations can be taken into account

ECOLL(L) - Array containing the average electric field intensity at the plate in the different grid strips which cover an area between successive wires (V/m)

L2 - Index which runs over the different grid strips in the basic area for which the calculations are performed

I1 - Number of the first grid strip in the last (NY-1) grid strips in a given wire-to-wire spacing

I2 - Number of the last grid strip in a given wire-to-wire spacing

I - Index which runs over and numbers the last (NY-1) grid strips in a given wire-to-wire spacing

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CHARGN USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

H - Increment size used in the Runge-Kutta scheme (sec)

H2 - One-half the increment size chosen for the Runge-Kutta scheme (sec)

YI - Time at the start of a given increment or subincrement of the precipitator (sec)

Y - Time at the end of a given increment or subincrement of the precipitator (sec)

XI - Number of charges on a given particle size at the start of a given increment or subincrement of the precipitator

X - Number of charges on a given particle size at the end of a given increment or subincrement of the precipitator

I - Index which runs over the different points specified for use in the Runge-Kutta scheme

NN - Number of points specified for use in the Runge-Kutta scheme

ECHARG - Elementary charge unit (coul)

SCHARG - Saturation charge number from the field charging equation

NUMINC - Number of increments in the Simpson's Rule integration over θ in equation (12)

CONST - Value of the quantity $[2(K-1)a^3E_0/(K+2)]$ found in equation (12) $[V\text{-}m^2]$

EZERO - Average electric field used for particle charging (V/m)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (12)

RSIZE - Radius of a particular particle (m)

ECONST - Value of the quantity $[3eE_0 a/kT(K+2)]$ found in equation (12)

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $[\text{coul}^2/\text{nt-m}^2]$

RR - Value of the quantity $[eE_0/kT]$ found in equation (12) $[m^{-1}]$

FCONST - Value of the quantity $[(K-1)eE_0 a^3/kT(K+2)]$ found in equation (12) $[m^2]$

FACTOR - Value of the quantity $[\pi\bar{v}a^2/2]$ found in equation (12) $[m^3/\text{sec}]$

COEFF - Value of the quantity $[bqs/4\varepsilon_0]$ found in equation (12) $[m^3/\text{sec}]$

AFID - Average reduced free ion density for particle charging in a particular length increment $(\#/m^3)$

T1 - Value of the charge-number rate to the particle surface at the point (XI,YI) multiplied by the stepsize H for use in the Runge-Kutta scheme

T2 - Value of the charge-number rate to the particle surface at the point (XI+H2, YI+T1/2) multiplied by the stepsize H for use in the Runge-Kutta scheme

T3 - Value of the charge-number rate to the particle surface at the point (XI+H2, YI+T2/2) multiplied by the stepsize H for use in the Runge-Kutta scheme

T4 - Value of the charge-number rate to the particle surface at the point (XI+H, YI+T3) multiplied by the stepsize H for use in the Runge-Kutta scheme

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR STATEMENT FUNCTION RATE USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

ECHARG - Elementary charge unit (coul)

SCHARG - Saturation charge number from the field charging equation

NUMINC - Number of increments in the Simpson's Rule integration over Θ in equation (12)

CONST - Value of the quantity $[2(K-1)a^3E_0/(K+2)]$ found in equation (12) $[V\text{-}m^2]$

EZERO - Average electric field used for particle charging (V/m)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (12)

RSIZE - Radius of a particular particle (m)

ECONST - Value of the quantity $[3eE_0a/kT(K+2)]$ found in equation (12) $[V\text{-}m^2]$

CMKS - Value of the quantity $[4\pi\varepsilon_0]$ found in equation (12) $[coul^2/nt\text{-}m^2]$

RR - Value of the quantity $[eE_0/kT]$ found in equation (12) $[m^{-1}]$

FCONST - Value of the quantity $[(K-1)eE_0a^3/kT(K+2)]$ found in equation (12) $[m^2]$

FACTOR - Value of the quantity $[\pi\tilde{v}a^2/2]$ found in equation (12) $[m^3/sec]$

COEFF - Value of the quantity $[bqs/4\varepsilon_0]$ found in equation (12) $[m^3/sec]$

AFID - Average reduced free ion density for particle charging in a particular length increment $(\#/m^3)$

NTIME - Instantaneous charging time (sec)

NUMBER - Instantaneous number of charges on a given particle size

INTGRL - Value of the integral appearing in equation (12)

NE - Negative of the instantaneous charge on a given particle size (coul)

THZERO - Maximum angle (θ_0) for field charging in radians

DELTAX - Increment size taken for the integration over the angle θ in equation (12)

THETA - Values of the angle θ taken for the integration over θ in equation (12)

SUMODD - Sum of the odd terms contributing to the integral in the Simpson's Rule integration scheme

J - Index which runs over the different points in the Simpson's Rule integration

CTHETA - Value of the quantity [$\cos\theta$]

TCONST - Value of the quantity [$2(K-1)a^3E_0\cos\theta/(K+2)$] ($m^2$-V)

ECOS - Value of the quantity [$E_0 \cos\theta$] (V/m)

C1 - Value of the quantity [$q/4\pi\varepsilon_0E_0\cos\theta$] found in equation (52)

CO - Value of the quantity [$(K-1)a^3/(K+2)$] found in equation (52) [m^3]

RZERO - Radial distance from the center of a given particle at which the total radial component of the electric field is zero (m)

ARG1 - Argument of the exponential function inside the integral in equation (12)

YVAL - Integrand of the integral in equation (12)

SUMEVN - Sum of the even terms contributing to the integral in the Simpson's Rule integration

CTZERO - Value of the quantity [$\cos\theta_0$]

ARG2 - Argument of the exponential function inside the integral in equation (12) for the angle θ_0

ZVAL - Contribution to the integral in equation (12) which depends on the angle θ_0

RATE1 - Contribution to the particle charging rate due to the second term in equation (12) [#/sec]

ARG3 - Argument of the exponential function in the third term in equation (12)

RATE2 - Contribution to the particle charging rate due to the third term in equation (12)

RATE3 - Contribution to the particle charging rate due to the first term in equation (12) [#/sec]

RATE - Total instantaneous charging rate to the entire surface of a given particle (#/sec)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ARCCOS USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

A - Numerator of the ratio A/B whose inverse cosine is to be determined

B - Denominator of the ratio A/B whose inverse cosine is to be determined

ACOS - Value of the quantity $[\cos^{-1}(A/B)]$ (radians)

RATIO - Value of the ratio A/B

T - Variable used to generate the different numerical coefficients in the series representation of the inverse cosine function

SUM - Sum of successive terms in the series representation of the inverse cosine function

TERM - A particular term in the series representation of the inverse cosine function

U - Variable used in the generation of the numerical coefficients in the series representation of the inverse cosine function

V - Variable used in the generation of the numerical coefficients in the series representation of the inverse cosine function

W - Variable used in the generation of the numerical coefficients in the series representation of the inverse cosine function

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ZERO USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

C1 - Value of the quantity $[q/4\pi\varepsilon_0 E_0\cos\theta]$ found in equation (52)

C0 - Value of the quantity $[(K-1)a^3/(K+2)]$ found in equation (52) $[m^3]$

RZERO - Radial distance from the center of a given particle at which the total radial component of the electric field is zero (m)

B - Value of the argument of the inverse cosine function found in equation (55)

C - Value of the inverse cosine function found in equation (55)

D - Factor multiplying the cosine function found in equation (12)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CHGSUM USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

I - Index which runs over incremental lengths

II - Index which runs over subincremental lengths

OLDQF(J) - Value of field charge on the different particle sizes at the end of a given increment or subincrement (coul)

OLDQT(J) - Value of diffusion charge on the different particle sizes at the end of a given increment or subincrement (coul)

ITER - Counter which keeps track of the number of iterations which is limited by NITER

SOLDQF(J) - Value of field charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

SOLDQT(J) - Value of diffusion charge on the different particle sizes at the start of an increment which must be saved for the iteration procedure over subincrements in a given increment (coul)

E - Elementary charge unit (coul)

SCHARG - Saturation charge number from the field charging equation

SATCHG - Saturation charge for a given particle size from field charging theory (coul)

CHRFID - Average free ion density for particle charging ($\#/m^3$)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

EPSO - Permittivity of free space ($coul^2/nt\text{-}m^2$)

TIMEF - Final value of time for particle charging (sec)

TIMEI - Initial value of time for particle charging (sec)

CF1 - Value of the quantity $[(N_0 be/4\varepsilon_0)(t_f - t_i)]$ found in equation (15)

CF2 - Value of the quantity $[1/(1-q_i/q_s)]$ found in equation (15)

QF - Charge on a given particle size in a given increment or subincrement due to field charging (coul)

V - Value of the quantity $[e^2/4\pi\varepsilon_0 akT]$ found in equation (15)

ARG - Value of the quantity $[q_i e/4\pi\varepsilon_0 akT]$ found in equation (15)

RSIZE - Radius of a particular particle (m)

VAVC - Root mean square velocity of the ions (m/sec)

BC - Boltzmann's constant (J/°K)

TDK - Temperature of the gas in a given electrical section (°K)

QT - Charge on a given particle size in a given increment or subincrement due to diffusion charging (coul)

CNUMBR - Total charge number on a given particle size in a given increment or subincrement

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTINC USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NPRINT - Indicator which designates when to print certain sectionalized data

NSECT - Indicator which keeps track of which electrical section the calculation is in

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

ITL - Identifying label for the calculations

SLNGTH - Length of a particular electrical section (m)

A - Collection plate area of a particular linear electrical section (m^2)

VO - Applied voltage in a particular linear electrical section (V)

TC - Total current in a particular linear electrical section (A)

B - Wire-to-plate spacing in a particular linear electrical section (m)

AC - Corona wire radius in a particular linear electrical section (m)

WL - Total wire length in a particular linear electrical section (m)

CL - Total current per length of corona wire in a particular linear electrical section (A/m)

CD - Average current density at the plate in a particular linear electrical section (A/m^2)

ET - Average electric field in the deposited particulate layer in a particular linear electrical section (V/m)

SY - One-half the wire-to-wire spacing in a particular linear electrical section (m)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

VGAS - Gas velocity in a particular linear electrical section (m/sec)

TDK - Temperature of the gas in a given electrical section (°K)

P - Gas pressure in a particular linear electrical section (atm)

VIS - Gas viscosity in a particular linear electrical section (kg/m-sec)

U - Ion mobility adjusted for temperature and pressure (m^2/V-sec)

VAVC - Root mean square velocity of the ions (m/sec)

TMFP - Ionic mean free path multiplied by a factor (m)

W - Total weight of particles per second passing into a particular linear electrical section (kg/sec)

LINC - Length of the increments taken in a particular linear electrical section (m)

XPI - Overall mass collection efficiency per increment based on the estimated or design efficiency (%)

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

RIOVR - Ratio of the ionic space charge density to the total space charge density

ERAVG - Average electric field used for particle charging (V/m)

EPLT - Absolute value of the average electric field at the plate in a particular length increment (V/m)

AFID - Average reduced free ion density for particle charging in a particular length increment (#/m^3)

XCD - Average current density at the plate in a particular length increment (nA/cm^2)

ZMD - Interpolated mass median diameter of the collected particulate layer (m)

WT - Total weight of material per cubic meter of gas removed in all particle size bands in a given length increment (kg/m^3)

LTHICK - Thickness of the collected particulate layer in a particular increment of length (mm/min)

JPART - Current density due to particles in a particular increment of length (A/m^2)

JION - Current density due to ions in a particular increment of length (A/m^2)

I - Index which runs over incremental lengths

ROVRI - Ratio of the total space charge density to the ionic space charge density

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTCHG USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

NCALC - Indicator which determines whether to use equation (12) for particle charging or the sum of the classical field and diffusion charges

NEST - Indicator which specifies whether to use extensive calculations or estimation procedures in determining precipitator performance

JS - Index which is utilized in dividing the output data for particle charging into sets of eight columns each with a column for each particle size band

KS - Index which is utilized in dividing the output data for particle charging into sets of eight columns each with a column for each particle size band

NS - Number of different particle size bands in the inlet particle size distribution

DIAM(J) - Diameters of the different particle sizes (μm and m)

J - Index which runs over the different particle size bands

I - Index which runs over incremental lengths

NF - Number of increments taken along the length of the precipitator

NVI - Indicator which specifies whether to base the electrical calculation on known voltages and currents or on calculated voltage-current characteristics

NI - Number of subincremental lengths into which the incremental length is divided

N - Number of the subincremental strip having the maximum values of average electric field and current density

PI - Value of the constant π

EPSO - Permittivity of free space (coul^2/nt-m^2)

RAD(J) - Radii of the different particle sizes (m)

TMFP - Ionic mean free path multiplied by a factor (m)

EAVG(N) - Average electric fields for particle charging in subincremental lengths (V/m)

EPS - Relative dielectric constant of the particles

VRATIO - Ratio of the peak applied voltage to the average for use in particle charging

XDC(I,J) - Charge on each particle size at the end of each increment (coul)

QSATM - Saturation charge for a given particle size based on the last electrical section and the subincremental strip containing the largest values of average electric field and current density (coul)

YY(J) - Array containing the ratio of the charge on a given particle size to the saturation charge in the last electrical section for a given increment

QSAT(J) - Saturation charge for a given particle size based on the last electrical section and the average electric field for the entire section (coul)

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE ADJUST USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

NRUN - Indicator that specifies which set of nonideal conditions is under consideration

NS - Number of different particle size bands in the inlet particle size distribution

NS1 - Number of particle size bands plus one

NUMSEC - Number of linear electrical sections in the precipitator

NUMS1 - Number of electrical sections less one

TDK - Temperature of the gas stream in the last electrical section (°K)

PS(NUMSEC) - Pressure of the gas stream in the last electrical section (atm)

CONVF - Conversion factor which converts kg/ACM to mg/DSCM

NRAPDC - Counter which keeps track of the number of rapping puff particle size distributions that have been considered

X - Ideal, unadjusted overall mass collection fraction (or efficiency) [no units or %]

I - Index which runs over the different particle size bands

DXS(I) - Total number of particles removed per cubic meter of gas in each particle size band under ideal conditions and with no empirical corrections (#/m^3)

ONO(I) - Initial number of particles per cubic meter of gas in each particle size band (#/m^3)

EFESR - Ideal, unadjusted mass collection fraction for a given particle size

PCNT(I) - Percentage or fraction by mass in the inlet particle size distribution of the different size bands (% and decimal)

ARD50(J) - Rapping puff mass median diameters (μm)

ARSIGM(J) - Rapping puff geometric standard deviations

RMMD - Particular value of ARD50(J)[μm]

RSIGMA - Particular value of ARSIGM(J)

RPRCU(I) - Cumulative fraction by mass as a function of particle size for the rapping puff

RPCNT(I) - Percentages by mass in the different particle size bands for the rapping puff (%)

NONCK - Counter which keeps track of the number of sets of nonideal conditions of nonuniform velocity distribution and gas sneakage and/or particle reentrainment without rapping that have been considered

ASNUCK(K) - Fractions of gas sneakage and/or particle reentrainment without rapping

SNUCK - Particular value of ASNUCK(K)

AZIGGY(K) - Normalized standard deviations of the gas velocity distribution

ZIGGY - Particular value of AZIGGY(K)

AZNUMS(K) - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur

ZNUMS - Number of stages over which gas sneakage and/or particle reentrainment without rapping occur for a particular case

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

Y - Adjusted overall mass collection fraction (or efficiency) under no-rap conditions (no units or %)

XEP - Adjusted mass collection fraction for a given particle size band under no-rap conditions

XMV(I) - Effective migration velocities for the different particle sizes under ideal conditions and with no empirical corrections (m/sec)

WY - Adjusted migration velocity for a given particle size under no-rap conditions (cm/sec)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

ATOTAL - Total collection plate area of the precipitator (m^2)

F1 - Correction factor for the migration velocity of a given particle size in order to account for nonuniform velocity distribution

F2 - Correction factor for the migration velocity of a given particle size in order to account for gas sneakage and/or particle reentrainment without rapping

WYS - Migration velocity of a given particle size corrected only for gas sneakage and/or particle reentrainment without rapping (cm/sec)

WYV - Migration velocity of a given particle size corrected only for nonuniform velocity distribution (cm/sec)

ZNLFF - Combined correction factor for nonuniform velocity distribution and gas sneakage and/or particle reentrainment without rapping

WYSV - Migration velocity of a given particle size corrected only for nonuniform gas velocity distribution and gas sneakage and/or particle reentrainment without rapping (cm/sec)

WUNCOR(I) - Unadjusted, ideal migration velocities for the different particle sizes (cm/sec)

EUNCOR(I) - Unadjusted, ideal mass collection efficiencies for the different particle sizes (%)

DIAM(I) - Diameters of the different particle sizes (μm and m)

PXS(I) - Number of particles per cubic meter of gas for a given particle size that are removed by the precipitator under adjusted, no-rap conditions (#/m^3)

IDC - Indicator which controls when the summation of outlet emissions over the different particle size bands will be performed

SPO - Total outlet emissions under adjusted, no-rap conditions (#/m^3)

SCPO - Total outlet emissions under rap + no-rap conditions (#/m^3)

IX - Indicator which determines when the total electrical length up to the last electrical section will be calculated

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%)

XY - Percentage by mass in a given particle size in the inlet particle size distribution (%)

PENTR - Percentage by mass of a given particle size that penetrates through the precipitator under adjusted, no-rap conditions (%)

PCTOT(I) - Percentage by mass in a given particle size band in the no-rap outlet emissions (%)

CLPTLS - Total electrical length of the precipitator excluding the last electrical section (m)

IS - Index which runs over the different linear electrical sections

LSECT(IS) - Number of length increments in the different linear electrical sections

LINCS(IS) - Lengths of the increments taken in the different linear electrical sections (ft)

NYX - Index which starts and terminates a loop in which the mass loss due to rapping and the mass leaving the precipitator under no-rap conditions are determined

XEFF - Overall mass collection fraction for either unadjusted, ideal or adjusted, no-rap conditions

NEFF - Indicator which determines whether the unadjusted, ideal or adjusted, no-rap efficiency is used to determine the mass reentrained due to rapping

EXPONT - Argument of the exponential function in equation (2) for either the unadjusted, ideal efficiency or the adjusted, no-rap efficiency

DL - Inlet mass loading (kg/m^3)

PL - Total electrical length of the precipitator (m)

XMELS - Mass entering the last section of the precipitator from either unadjusted, ideal or adjusted, no-rap calculations (kg/m^3)

XMCLS - Mass collected in the last section of the precipitator from either unadjusted, ideal or adjusted, no-rap calculations (kg/m^3 or mg/DSCM)

XMLLS - Mass leaving the last section of the precipitator from either unadjusted, ideal, or adjusted, no-rap calculations (kg/m^3)

NTEMP - Indicator which specifies whether the precipitator is cold or hot side

RAPLOS - Mass contained in the outlet emissions due to rapping (mg/DSCM)

YMELS - Mass entering the last section of the precipitator from adjusted, no-rap calculations (kg/m^3)

YMCLS - Mass collected in the last section of the precipitator from adjusted, no-rap calculations (kg/m^3 or mg/DSCM)

YMLLS - Mass leaving the last section of the precipitator from adjusted, no-rap calculations (kg/m^3)

DD - Mass density of the particles (kg/m^3)

RNS - Number of particles per cubic meter of gas in a given size band that are contained in the emissions due to rapping ($\#/m^3$)

EFFWR - Mass collection fraction for a given particle size containing all corrections and adjustments

CRNP - Number of particles per cubic meter of gas in a given size band that are collected after rapping ($\#/m^3$)

COREFF - Mass collection efficiency for a given particle size containing all corrections and adjustments (%)

WYP - Migration velocity for a given particle size containing all corrections and adjustments (cm/sec)

CPENTR - Percent penetration of a given particle size containing all corrections and adjustments (%)

CPCTOT(I) - Percentage by mass in a given size band contained in the no-rap + rap emissions (%)

SL - Number of particles per cubic meter of gas of a given particle size band exiting the precipitator under no-rap conditions ($\#/m^3$)

RAD(I) - Radii of the different particle sizes (m)

WSL(I) - Weight per cubic meter of gas of particles in a given size band exiting the precipitator under no-rap conditions (kg/m^3)

ENDPT(I) - Particle diameters in the inlet cumulative percent by mass distribution (μm and m)

DLD - Value of the quantity $[\Delta\log_{10}D]$ for a given particle size band in the size distribution histogram

DMDLD(I) - Value of the quantity $[\Delta M/\Delta\log_{10}D]$ for the different particle size bands in the outlet emissions under no-rap conditions (mg/DSCM)

RDMDLD(I) - Value of the quantity $[\Delta M/\Delta\log_{10}D]$ for the different particle size bands in the outlet emissions due to rapping only (mg/DSCM)

CDMDLD(I) - Value of the quantity $[\Delta M/\Delta\log_{10}D]$ for the different particle size bands in the outlet emissions under no-rap + rap conditions (mg/DSCM)

CCF(I) - Cunningham correction factor for the different particle sizes

ETAO - Estimated or design overall mass collection efficiency (%)

ZMMDI - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMI - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

NDIST - Indicator which specifies whether the user is to supply the inlet particle size distribution or the program is to calculate a log-normal distribution

GFIT - Linear-correlation coefficient obtained in the log-normal fit of the inlet particle size distribution

PRCUNR(I) - Cumulative percentage by mass as a function of particle size for the outlet emissions under no-rap conditions (%)

SUMNR - Summation over the different particle size bands of the percentage by mass contained in each size band for the outlet emissions under no-rap conditions (%)

ZMDL - Fitted mass median diameter of the outlet no-rap emissions based on a log-normal distribution (μm)

SIGMO - Fitted geometric standard deviation of the outlet no-rap emissions based on a log-normal distribution

ZGFIT - Linear-correlation coefficient obtained in the log-normal fit of the outlet no-rap emissions

COREFW - Precipitation rate parameter under no-rap + rap conditions (cm/sec)

WZ - Precipitation rate parameter under no-rap conditions (cm/sec)

PRCUC(I) - Cumulative percentage by mass as a function of particle size for the outlet emissions under no-rap + rap conditions (%)

SUMC - Summation over the different particle size bands of the percentage by mass contained in each size band for the outlet emissions under no-rap + rap conditions (%)

CZMDL - Fitted mass median diameter of the outlet no-rap + rap emissions based on a log-normal distribution (μm)

CSIGMO - Fitted geometric standard deviation of the outlet no-rap + rap emissions based on a log-normal distribution

CGFIT - Linear-correlation coefficient obtained in the log-normal fit of the outlet no-rap + rap emissions

M - Index which runs over the different particle size bands

NONID - Number of nonideal conditions of gas velocity nonuniformity and gas sneakage and/or particle reentrainment without rapping to be considered

NRAPD - Number of rapping puff particle size distributions to be considered

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE WADJST USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DIAM(I) - Diameters of the different particle sizes (μm and m)

I - Index which runs over the different particle size bands

WY - Enters the subroutine as the unadjusted, no-rap migration velocity for a given particle size and leaves as the adjusted, no-rap migration velocity (cm/sec)

ONO(I) - Initial number of particles per cubic meter of gas in each particle size band (#/m^3)

PXS(I) - Number of particles per cubic meter of gas for a given particle size that are removed by the precipitator under adjusted, no-rap conditions (#/m^3)

ATOTAL - Total collection plate area of the precipitator (m^2)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

EFESR - Mass collection fraction for a given particle size under adjusted, no-rap conditions

CFACT(L) - Correction factors for the no-rap migration velocities of the different particle sizes

DCHECK(L) - Particle diameters corresponding to the different correction factors given by CFACT(L) [m]

L - Index which runs over the different values of CFACT(L) and DCHECK(L)

WFACT - Interpolated correction factor for the unadjusted, no-rap migration velocity of a given particle size

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE LNDIST USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

D50 - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMAP - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

PRCU(I) - Cumulative fractions by mass up to specified particle sizes

PCNT(J) - Fractions by mass contained in specified particle size bands

Y(K) - Values of the log-normal distribution function at different values of the independent variable for use in integrating the function over the specified size bands

Z(K) - Cumulative integrals resulting from the integration of the log-normal distribution function over a specified particle size band

AREA(J) - Amount of the distribution accumulated in a given particle size band

NS - Number of particle size bands

ENDPT(I) - Particle diameters specified for use in constructing the log-normal distribution histogram (μm)

NENDPT - Number of particle diameters specified for use in constructing the log-normal distribution histogram

PI - Value of the constant π

SIGMAZ - Value of the quantity $[\ln \sigma_\rho]$

N - Total number of particle size bands used in constructing the log normal distribution histogram

NINC - Number of points used in the Trapezoidal Rule integrations over the different particle size bands

ASUM - Value of the integration of the log-normal distribution function over the entire distribution

K - Index which runs over the NS different particle size bands specified by the user

J - Index which runs over the N different particle size bands used in the construction of the log-normal distribution histogram

X2 - Upper limit of integration for a given particle size band

X1 - Lower limit of integration for a given particle size band

DX - Stepsize taken for the Trapezoidal Rule integration of the log-normal distribution function over the different particle size bands

D - Value of the integration variable at different points in a given particle size band

SGT1 - Value of the quantity $[1/\sigma_z\sqrt{2\pi}]$

SGT2 - Value of the quantity $[2\sigma_z^2]$

I - Index which runs over the different points in a given particle size band in performing the Trapezodial Rule integration of the log-normal distribution function

SUM - Total fraction by mass contained in the histogram specified by the user

CHECK1 - Difference between 1 and the calculated total mass fraction contained in the histogram specified by the user

CHECK2 - Difference between 1 and the calculated cumulative fraction by mass up to the largest particle size specified by the user

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE QTFE USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

DX - Stepsize used in the Trapezoidal Rule integration scheme

Y(I) - Function values used in the integration scheme

Z(I) - Cumulative integrals resulting from the integration scheme

NINC - Number of points used in the integration scheme

SUM2 - Cumulative integral up to a given point in the integration scheme

DDX - One-half of the specified stepsize

I - Index which runs over the different points in the integration scheme

SUM1 - Cumulative integral up to the point prior to the point under consideration

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE LNFIT USED IN THE ELECTRISTATIC PRECIPITATOR PERFORMANCE MODEL

PRCU(I) - Known or calculated cumulative percentages supplied by the user (%)

D50 - Fitted mass median diameter based on a log-normal distribution (μm)

SIGMAP - Fitted geometric standard deviation based on a log-normal distribution

GFIT - Linear-correlation coefficient obtained in the log-normal fit

Z(I) - Natural logarithm of the actual particle diameters corresponding to the known or calculated cumulative percentages

Y(I) - Calculated natural logarithm of the particle diameters corresponding to the known or calculated cumulative percentages based on a true log-normal distribution

ENDPT(I) - Actual particle diameters corresponding to the known or calculated cumulative percentages (μm)

NENDPT - Number of particle diameters corresponding to the known or calculated cumulative percentages

NSTAG - Number of points used in the log-normal fit procedure

I - Index which runs over the different particle diameters corresponding to the known or calculated cumulative percentages

J - Index which sequences the points which are actually used in the log-normal fit

XY - Cumulative mass fraction less than a given particle size

XYY - Square root of the natural logarithm of the square of the reciprocal of XY

A - Y-intercept of the fitted straight line

B - Slope of the fitted straight line

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE CFIT USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

A - Y-intercept of the fitted straight line

B - Slope of the fitted straight line

R - Linear-correlation coefficient for the straight line fit

NSTAG - Number of data points that are fitted to the straight line

Z(I) - Values of the independent variable

Y(I) - Values of the dependent variable

XN - Running sum over the number of data points

SUMX - Summation over all data points of the values of the independent variable

SUMY - Summation over all data points of the values of the dependent variable

SUMXY - Summation over all data points of the values of the product of the independent and dependent variables

SUMXX - Summation over all data points of the values of the square of the independent variable

SUMYY - Summation over all data points of the values of the square of the dependent variables

I - Index which runs over the different data points

LIST OF NECESSARY VARIABLES, DEFINITIONS, AND UNITS FOR SUBROUTINE PRTSUM USED IN THE ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

ATOTAL - Total collection plate area of the precipitator (m^2)

VG - Gas volume flow rate in a particular electrical section (m^3/sec)

SCA - Specific collection area of the precipitator (m^2/m^3/sec)

VOSUM - Sum of the applied voltages in the different linear electrical sections (V)

CDSUM - Sum of the current densities in the different linear electrical sections (nA/cm^2)

NUMSEC - Number of linear electrical sections in the precipitator

LSECT(I) - Number of length increments in the different linear electrical sections

LINCS(I) - Lengths of the increments taken in the different linear electrical sections (ft)

I - Index which runs over the different linear electrical sections

VOS(I) - Applied voltages for the different linear electrical sections (V)

TCS(I) - Total current for the different linear electrical sections (A)

AS(I) - Collection plate areas for the different linear electrical sections (m^2)

AVO - Average applied voltage over the entire precipitator (V)

PL - Total electrical length of the precipitator (ft and m)

ACD - Average current density over the entire precipitator (nA/cm^2)

RHO - Resistivity of the collected particulate layer (ohm-m)

RHOCGS - Resistivity of the collected particulate layer (ohm-cm)

NPRNT - Indicator which specifies the unit number of the output device for printing data from the program

NRUN - Indicator that specifies which set of nonideal conditions is under consideration

SCOREF - Overall mass collection efficiency under no-rap + rap conditions (%)

ZMMDI - Specified or fitted mass median diameter of the inlet particle size distribution based on a log-normal distribution (μm)

SIGMI - Specified or fitted geometric standard deviation of the inlet particle size distribution based on a log-normal distribution

CZMDL - Fitted log-normal mass median diameter of the outlet particle size distribution under no-rap + rap conditions (μm)

CSIGMO - Fitted log-normal geometric standard deviation of the outlet particle size distribution under no-rap + rap conditions

SNUCK - Particular value of ASNUCK(JJ)

ZIGGY - Particular value of AZIGGY(JJ)

RMMD - Particular value of ARD50(II) [μm]

RSIGMA - Particular value of ARSIGM(II)

APPENDIX C

COMPLETE LISTING OF THE COMPUTER PROGRAM

```
C                 ***********************************
C                 *                                 *
C                 *        E.P.A. ESP MODEL         *
C                 *                                 *
C                 *  I.E.R.L.-R.T.P. AND SO.R.I.    *
C                 *                                 *
C                 *    REVISION I,JAN. 1, 1978      *
C                 *                                 *
C                 ***********************************
      REAL  NWIRE,LTHICK,JPART,JION,LINC,NWS,LINCS
      INTEGER VISKIP,VISAME
      DIMENSION CHKSUM(20)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK4/NS
      COMMON/BLK5/ZMMDT,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK7/XDC(45,20)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK9/ECOLL(30)
      COMMON/BLK10/ECLFAN(30)
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK13/VCOOP(15,15)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK15/NPRINT,NSECT,SLNGTH,A,VO,TC,B,AC,WL,CL,CD,ET,SY,
     1VGAS,P,VIS,W,LINC,XPI,RIOVR,EPLT,AFID,XCD,ZMD,
     2WT,LTHICK,JPART,JION,I,ROVRI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK18/SCOREF,CZMDL,CSIGMO,NRUN,SNUCK,ZIGGY,RMMD,RSIGMA
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,ERD,NDSET,NWS(10),D50,SIGMAP
      COMMON/BLK20/SCHARG,CHRFID,TIMEI,TIMEF,V,FACTRE,RSIZE,CNUMBR,J,II,
     1ITER,OLDQF(20),OLDQT(20),SOLDQF(20),SOLDQT(20)
      EXTERNAL RATE
      NREAD=2
      NPRNT=3
C
C   CONSTANTS
C
      PI = 3.1415927
      E = 1.6E-19
      BC=1.38E-23
      EPSO = 8.85E-12
      CHKS=4.*PI*EPSO
 4000 CONTINUE
C
C
      NDSET=0
      READ(NREAD,5) NENDPT,NDATA
    5 FORMAT(2I2)
      IF(NENDPT-99) 4500,9999,9999
 4500 CONTINUE
```

```
      NS=NENDPT-1
      READ(NREAD,7) ITL
    7 FORMAT(40A2)
      GO TO(9400,9401,9402,9403),NDATA
 9400 CONTINUE
      READ(NREAD,4864) NEST,NDIST,NVI,NX,NY,NITER,NCALC,NRAPD,NEFF,
     1NTEMP,NONID
 4864 FORMAT(11I2)
      IF(NCALC.EQ.0) READ(NREAD,5) NN,NUMINC
      IF(NVI.EQ.2) READ(NREAD,8530) IFINAL,JI1,JI2,VISKIP,VISAME
 8530 FORMAT(5I2)
      READ(NREAD,6) DL,PL,ETAO,DD,FPS,VRATIO,US,FPATH,EBD,RHO
    6 FORMAT(9F8.0,E8.2)
C
C         CONVERSION
C
      PL = PL * 0.305
      DL = DL * 2.29E-03
      RHO = RHO/100.0
      DV = DL / DD
C
      IF(NRAPD.GT.1) READ(NREAD,8531) (ARD50(I),ARSIGM(I),I=2,NRAPD)
 8531 FORMAT(10(2F4.0))
      READ(NREAD,8532) (ASNUCK(I),AZIGGY(I),AZNUMS(I),I=1,NONID)
 8532 FORMAT(6(3F4.0))
      READ(NREAD,4) (ENDPT(I),I=1,NENDPT)
    4 FORMAT(10F8.0)
      DO 4740 I=1,NS
      DIAM(I)=((ENDPT(I)+ENDPT(I+1))/2.)*1.E-06
      RAD(I)=DIAM(I)/2.
 4740 CONTINUE
 9401 CONTINUE
      IF(NDIST.EQ.2) READ(NREAD,8533) D50,SIGMAP
 8533 FORMAT(2F8.0)
      IF(NDIST.EQ.1) READ(NREAD,4) (PRCU(I),I=1,NENDPT)
      IF(NDIST.EQ.2) GO TO 8521
      DO 3 I=1,NS
      PCNT(I)=(PRCU(I+1)-PRCU(I))*1.E-02
    3 CONTINUE
      CALL LNFIT(PRCU,D50,SIGMAP,GFIT)
      ZMMDI=D50
      SIGMI=SIGMAP
      GO TO 8522
 8521 CONTINUE
      CALL LNDIST(D50,SIGMAP,PRCU,PCNT)
      ZMMDI=D50
      SIGMI=SIGMAP
 8522 CONTINUE
      IF(NDATA.GT.1) GO TO 8534
      READ(NREAD,770) NUMSEC,(LSECT(I),I=1,NUMSEC)
  770 FORMAT(I2,10I2)
      DO 1143 NSECT=1,NUMSEC
      READ(NREAD,762) AS(NSECT),VOS(NSECT),TCS(NSECT),WLS(NSECT),
     1ACS(NSECT),BS(NSECT),NWS(NSECT),SYS(NSECT),VGS(NSECT)
     2,VGASS(NSECT),TEMPS(NSECT),PS(NSECT),VISS(NSECT),LINCS(NSECT)
  762 FORMAT(7(E11.4))
      IF(NVI.EQ.1) GO TO 1143
      READ(NREAD,762) RFS(NSECT),START1(NSECT),START2(NSECT),START3
     1(NSECT),VSTAR(NSECT)
 1143 CONTINUE
```

```
      GO TO 8534
 9402 CONTINUE
      READ(NREAD,9410) (VGS(I),VGASS(I),I=1,NUMSEC)
 9410 FORMAT (3(2E11.4))
      GO TO 8534
 9403 CONTINUE
      READ(NREAD,9410) (VOS(I),TCS(I),I=1,NUMSEC)
 8534 CONTINUE
      LK=0
      WRITE(NPRNT,17)
   17 FORMAT('1')
      NI = 2*NV - 2
      NF=0
      DO 4649 KA=1,NUMSEC
      NF=NF+LSECT(KA)
 4649 CONTINUE
C
C
C
      DO 1 I = 1 ,NS
      VOL(I) = PCNT(I) * DV
    1 CONTINUE
      NPRINT=0
      IF(NVI.EQ.1) ITER=0
  305 CONTINUE
      IF(NVI.EQ.1) ITER=ITER+1
      DO 9 I = 1, NS
      DXS(I)=0.
      XNO(I) = VOL(I)/ ( 4./3. * PI * RAD(I)**3 )
      ONO(I) = XNO(I)
    9 CONTINUE
      CALL PRTINP
C
C
C************************************************************************
C
C        START  INCREMENTAL ANALYSIS OF PRECIPITATOR
C
C************************************************************************
C
      LK=1
      ZWT=0.
      RATIO=(EPS-1.)/(EPS+2.)
      G=EPS+2.
      INDEX=0
      NSECT=1
      NCOOP=0
      DO 3000 I=1,NF
      IF(NVI.EQ.2) ITER=0
      INDEX=INDEX+1
      IF(I.EQ.1) GO TO 761
      IF(INDEX-LSECT(NSECT)) 760,760,761
 761  CONTINUE
      NCOOP=1
      NPRINT=1
      IF(I.EQ.1) GO TO 760
      NSECT=NSECT+1
      INDEX=1
 760  CONTINUE
      IF(NCOOP.NE.1) GO TO 764
      A=AS(NSECT)*9.3E-02
      VO=VOS(NSECT)
      TC=TCS(NSECT)
      WL=WLS(NSECT)*0.305
      AC=ACS(NSECT)*2.54E-02
      SX=BS(NSECT)*2.54E-02
      SY=SYS(NSECT)*2.54E-02
      NWIRE=NWS(NSECT)
      VG=VGS(NSECT)*4.73E-04
      VGAS=VGASS(NSECT)*.305
      TEMP=TEMPS(NSECT)+459.
      P=PS(NSECT)
      VIS=VISS(NSECT)
      LINC=LINCS(NSECT)*0.305
      RF=RFS(NSECT)
      START=START1(NSECT)
      DSTART=START2(NSECT)
      CSTART=START3(NSECT)
      VSTART=VSTAR(NSECT)
      SLNGTH=FLOAT(LSECT(NSECT))*LINC
      B=SX
C
C CALCULATE ION MEAN FREE PATH
C
      TDK=TEMP/1.8
      ZMV=8.205E-05*TDK/P
      ZMFP=(8.205E-05*TDK)/(1.414*PI*1.6E-19*6.02E+23*P)
      TMFP=ZMFP*FPATH
      VAVG=SQRT((8.*8.314E+07*TDK)/(3.14*32.))
      VAVC=VAVG/100.
      VC=E**2/(BC*TDK)
      FACTRC=(PI*VAVC)/2.
C
C   COMPUTE ION MOBILITY CORRECTED FOR TEMPERATURE AND PRESSURE
C
      U=(TDK/273.16)*US*(1.0/P)
C
      COEFFC=PI*U*E
      TINC=LINC/VGAS
      IF(NVI.EQ.1) GO TO 4675
      DTINC = TINC/FLOAT(NI)
 4675 CONTINUE
C
C     COMPUTE WEIGHT OF DUST
C
      W = DL * VG
C
      DO 6993 J=1,NS
      CCF(J)=1+(ZMFP/RAD(J))*(1.257+.4*EXP(-1.1*RAD(J)/ZMFP))
 6993 CONTINUE
      IF(NVI.EQ.2) GO TO 4676
      ERAVG=VO/SX
      DO 6989 L=1,NS
      QSAT(L)=(4.*PI*EPS0*(RAD(L)+TMFP)**2)*ERAVG*(1.+2.*((EPS-1.)/
     1(EPS+2.))*(RAD(L)/(RAD(L)+TMFP))**3)*VRATIO
 6989 CONTINUE
      R=(E*ERAVG)/(BC*TDK*(EPS+2.))
      RR=(E*ERAVG)/(BC*TDK)
      RG=R*G
 4676 CONTINUE
```

```
      NCOOP=0
      IF(NVI.EQ.2) GO TO 4677
      IF(NEST.EQ.2) GO TO 4678
      VW=-1.*VO
      CALL CMAN(VW,NX,NY,SX,SY,PI,AC,NWIRE)
      GO TO 4678
 4677 CONTINUE
      UEQ=U
      NEC=0
      IF((VISAME.EQ.1).AND.(NSECT.GT.1)) GO TO 5564
      IF((VISAME.EQ.1).AND.(NDSET.GT.1)) GO TO 5564
      WRITE(NPRNT,7140) NSECT
 7140 FORMAT(//23X,'CLEAN GAS VOLTAGE-CURRENT DENSITY-FIELD AT THE PLATE
     1 RELATIONSHIP FOR SECTION NO. ',I2//)
      CALL EFLD2(UEQ,AC,VO,SX,SY,NX,NY,AEPLT,TDK,P,RF,START,
     1DSTART,CSTART,IFINAL,VSTART,VW,ACDNTY,NWIRE,NEC,ERD,JI1,JI2)
      DO 7919 NZ=1,NI
      ECLEAN(NZ)=ECOLL(NZ)
 7919 CONTINUE
      CDCLN=ACDNTY
 5564 CONTINUE
      VOS(NSECT)=-VW
 4678 CONTINUE
      IF(NVI.EQ.2) TC=CDCLN*A
C
C   COMPUTE CURRENT DENSITY
      CD = TC / A
C
C
C   COMPUTE ELECTRIC FIELD IN DEPOSIT
      ET = CD * RHO
C
C
C   COMPUTE CURRENT PER  M. OF CORONA WIRE
C
      CL = TC / WL
C
 764  CONTINUE
      IF(NVI.EQ.1) GO TO 4679
      ITER=ITER+1
      USUM=0.
      WSSUM=0.
      RHOSUM=0.
      GO TO 4680
 4679 CONTINUE
      CALL SPCHG1(SW,ROVRT,OROVRT,XS,ETAPF,DW,QSAT,XNO,W,LSECT,TC,VG,
     1ETAO,FID,AFID,AVGFID,XCD,U,UEQ,I,NSECT,LINC,PL,CD,E,ERAVG,NS,XPI)
      CHRFID=AFID
 4680 CONTINUE
C
C**********************************************************************
C
C          START PARTICLE SIZE LOOP
C
C**********************************************************************
C
      PROT=0.0
      WT = 0.
      JPART=0.
C
```

```
C     COMPUTE CHARGE ON EACH PARTICLE AFTER ONE INCREMENT OF TRAVEL
C
      IF(NVI.EQ.1) GO TO 4681
      II = 0
      SERAVG = 0.0
 6337 CONTINUE
      II = II + 1
      CHRFID=CHFID(II)
      ERAVG=EAVG(II)
      SERAVG = SERAVG + ERAVG/NI
      DO 9130 L=1,NS
      QSAT(L)=(4.*PI*EPSO*(RAD(L)+TMFP)**2)*ERAVG*(1.+2.*((EPS-1.)/
     1(EPS+2.))*(RAD(L)/(RAD(L)+TMFP))**3)*VRATIO
 9130 CONTINUE
      R=(E*ERAVG)/(BC*TDK*(EPS+2.))
      RR=(E*ERAVG)/(BC*TDK)
      RG=R*G
 4681 CONTINUE
      DO 2900 J = 1, NS
      IF(NVI.EQ.1) GO TO 4682
      OLDQ(J)=Q(J)
      IF(II.NE.1) GO TO 426
 4682 CONTINUE
      IF(I.NE.1) GO TO 426
      IF(J.GT.1) GO TO 428
      TIMEI=0.
      XIPC=0.
      IF(NVI.EQ.2) GO TO 4683
      TIMEF=TINC
      IF(NCALC.EQ.0) H=TINC/NN
      GO TO 4684
 4683 CONTINUE
      TIMEF=DTINC
      IF(NCALC.EQ.0) H=DTINC/NN
 4684 CONTINUE
      GO TO 428
  426 CONTINUE
      IF(NVI.EQ.1) GO TO 4685
      IF(J.GT.1) GO TO 429
      TIMEI=TIMEF
      IF((ITER.GT.1).AND.(II.EQ.1)) TIMEI=TIMEI-TINC
      TIMEF=TIMEF+DTINC
      IF(NCALC.EQ.0) H=DTINC/NN
  429 CONTINUE
      IF(II.NE.1) GO TO 8242
      XIPC=XDC(I-1,J)/1.6E-19
      GO TO 8243
 8242 CONTINUE
      XIPC=XDC(I,J)/1.6E-19
 8243 CONTINUE
      GO TO 4686
 4685 CONTINUE
      IF(J.GT.1) GO TO 4687
      TIMEI=FLOAT(I-1)*TINC
      TIMEF=FLOAT(I)*TINC
      IF(NCALC.EQ.0) H=TINC/NN
 4687 XIPC=XDC(I-1,J)/1.6E-19
 4686 CONTINUE
  428 CONTINUE
      PSIZE=RAD(J)
      SCHARG=QSAT(J)/1.6E-19
      DCONST=RATIO*RSIZE**3
      CONST=2.*DCONST*ERAVG
      S=3.*RSIZE
      V=VC/(RSIZE*CMKS)
      ECONST=S*R
      FCONST=RG*DCONST
      FACTRE=FACTRC*RSIZE**2
      COEFF=(COEFFC*SCHARG)/CMKS
      IF(I.LE.2) GO TO 5850
      IF(NVI.EQ.1) GO TO 5851
      IF((II.EQ.1).AND.(ITER.EQ.1)) GO TO 5851
      GO TO 5852
 5851 CONTINUE
      IF(I.EQ.3) GO TO 5853
      IF(NSECT.EQ.1) GO TO 5680
      IF((INDEX.EQ.1).AND.(VOS(NSECT).GT.VOS(NSECT-1))) GO TO 5850
 5680 CONTINUE
      IF(CHKSUM(J).LE.0.005) GO TO 5854
 5853 CONTINUE
      CHKSUM(J)=(XDC(I-1,J)-XDC(I-2,J))/XDC(I-1,J)
 5852 CONTINUE
      IF(NSECT.EQ.1) GO TO 5681
      IF((INDEX.EQ.1).AND.(VOS(NSECT).GT.VOS(NSECT-1))) GO TO 5850
 5681 CONTINUE
      IF(CHKSUM(J).GT.0.005) GO TO 5850
 5854 CONTINUE
      Q(J)=XDC(I-1,J)
      GO TO 5855
 5850 CONTINUE
      IF((NCALC.EQ.1).OR.(NEST.EQ.2)) GO TO 8180
      CALL CHARGN(E,SCHARG,NUMINC,CONST,ERAVG,V,RSIZE,ECONST,CMKS,RR,
     1FCONST,FACTRE,COEFF,CHRFID,RATE,H,TIMEI,XIPC,NN,CTIME,CNUMBR)
      GO TO 8181
 8180 CONTINUE
      CALL CHGSUM
 8181 CONTINUE
      Q(J)=CNUMBR*1.6E-19
      IF((TIMEI.EQ.0.).AND.(CNUMBR.GT.SCHARG)) Q(J)=SCHARG*1.6E-19
 5855 CONTINUE
      XDC(I,J)=Q(J)
      IF(NVI.EQ.1) GO TO 2900
C
C    COMPUTE MIGRATION VELOCITY FOR EACH SIZE RANGE
C
      EMV=(Q(J)*ECOLL(II))/(6.*PI*RAD(J)*VIS)
      IF(ITER.EQ.1) EMV=(Q(J)*ECLEAN(II))/(6.*PI*RAD(J)*VIS)
      EMV=CCF(J)*EMV
      XMV(J)=EMV
C
C    COMPUTE EFFICIENCY FOR EACH SIZE RANGE
C
      X=(-A*EMV)/(VG*FLOAT(LSECT(NSECT))*FLOAT(NI))
C
      EFF =  1. - EXP( X )
C
C      COMPUTE NUMBER OF PARTICLES REMOVED IN EACH SIZE RANGE
C
      IF(ITER.EQ.1) GO TO 3761
      IF(II.NE.1) GO TO 3763
      XNO(J)=OLDXNO(J)
      GO TO 3763
 3761 CONTINUE
      IF(II.NE.1) GO TO 3763
      OLDXNO(J)=XNO(J)
 3763 CONTINUE
      DXNO=XNO(J)*EFF
      IF(ITER.NE.NITER) GO TO 3765
      DXS(J)=DXS(J)+DXNO
      WSSUM=DXNO*(1,33333*PI*RAD(J)**3)*DD
      WS(J)=WS(J)+WSSUM
      WT=WT+WSSUM
C
C   CALCULATE THE CURRENT DENSITY AT THE PLATE DUE TO THE PARTICULATE
      JPART=JPART+(FLOAT(LSECT(NSECT))*VG*DXNO*Q(J)*FLOAT(NI))/A
 3765 CONTINUE
      XNO(J)=XNO(J)-DXNO
C
 2900 CONTINUE
      IF(NVI.EQ.1) GO TO 9131
      CALL SPCHG2(NS,XNO,VIS,RAD,LINC,E,U,ERAVG,DNSION,
     1DELTNP,SUMMOB,PNUM,RHOP,TCHRG,PMOB,TDNSP,RDNSI,AFID,UEQ,AVGFID,
     2RIOVR,I,XS,ETAO,PL,ETAPF,CCF,XPI,OLDQ,Q,II,NSECT)
      USUM=USUM+UEQ
      RHOSUM=RHOSUM+RIOVR
 5676 CONTINUE
      IF(II.LT.NI) GO TO 6337
      UEQ=USUM/FLOAT(NI)
      RIOVR=RHOSUM/FLOAT(NI)
      IF(I.EQ.1) GO TO 376
      IF(RIOVR.GT.0,99) GO TO 375
  376 CONTINUE
      IF((VISKIP.EQ.1).OR.(NEST.EQ.2)) GO TO 3187
      WRITE(NPRNT,7141) I
 7141 FORMAT(//23X,'DIRTY GAS VOLTAGE-CURRENT DENSITY-FIELD AT THE PLATE
     1 RELATIONSHIP FOR INCREMENT NO. ',I2//)
      NEC=1
      START=START1(NSECT)*(UEQ/U)
      CALL EFLD2(UEQ,AC,VO,SX,SY,NX,NY,AEPLT,TDK,P,RF,START,
     1DSTART,CSTART,IFINAL,VSTART,VW,ACDNTY,NWIRE,NEC,ERD,JI1,JI2)
      GO TO 3188
 3187 CONTINUE
      ACDNTY=CDCLN*(UEQ/U)
 3188 CONTINUE
      EPLT=-1.*AEPLT
      XCD=ACDNTY*100000.
  375 CONTINUE
      IF(ITER.NE.NITER) GO TO 1050
      IF(INDEX.EQ.1) SUMCD=0.
      IF(INDEX.EQ.1) SUMVO=0.
      SUMCD=SUMCD+ACDNTY
      SUMVO=SUMVO-VW
      IF(INDEX.EQ.LSECT(NSECT)) TCS(NSECT)=(SUMCD*A)/FLOAT(LSECT(NSECT))
      IF(INDEX.EQ.LSECT(NSECT)) VOS(NSECT)=SUMVO/FLOAT(LSECT(NSECT))
 1050 CONTINUE
      IF(ITER.LT.NITER) GO TO 764
      JPART=JPART/FLOAT(NI)
      GO TO 4688
 9131 CONTINUE
      IF(UEQ.LT.1.0E-4)UEQ=1.0E-4
      IF(INDEX.EQ.1) GO TO 377
      IF(UEQ.NE.1.0E-4) GO TO 9133
      IF(UEQ.EQ.1.0E-4)EPLT=SKIP
      GO TO 9132
 9133 CONTINUE
      SIGMA=OROVRI-ROVRI
      SIGMA=ABS(SIGMA)
      IF(SIGMA.LT..01) GO TO 9132
  377 CONTINUE
      IF(NEST.EQ.2) GO TO 8182
      CALL EFLD1(UEQ,CD,AC,VO,SX,SY,NX,NY,TDK,P,AEPLT,VERGE,CVERGE)
      EPLT=-1.*AEPLT
      GO TO 8183
 8182 CONTINUE
      EPLT=ERAVG/1.75
 8183 CONTINUE
      SKIP=EPLT
 9132 OROVRI=ROVRI
      DO 2965 J=1,NS
C
C    COMPUTE MIGRATION VELOCITY FOR EACH SIZE RANGE
C
      EMV=(Q(J)*EPLT)/(6.*PI*RAD(J)*VIS)
      EMV=CCF(J)*EMV
      XMV(J)=EMV
C
C    COMPUTE EFFICIENCY FOR EACH SIZE RANGE
C
      X=(-A*EMV)/(VG*FLOAT(LSECT(NSECT)))
C
      EFF =  1. - EXP( X )
C
C      COMPUTE NUMBER OF PARTICLES REMOVED IN EACH SIZE RANGE
C
      DXNO=XNO(J)*EFF
      DXS(J)=DXS(J)+DXNO
      WS(J)=DXNO*(1.33333*PI*RAD(J)**3)*DD
      XNO(J)=XNO(J)-DXNO
      WT=WT+WS(J)
C
C   CALCULATE THE CURRENT DENSITY AT THE PLATE DUE TO THE PARTICULATE
      JPART=JPART+(FLOAT(LSECT(NSECT))*VG*DXNO*Q(J))/A
C
 2965 CONTINUE
 4688 CONTINUE
      ZWT=ZWT+WT
C
C   CALCULATE THE CURRENT DENSITY AT THE PLATE DUE TO IONS
      JION=CD-JPART
C
C
C   CALCULATE THICKNESS OF DUST LAYER IN (MM/MIN)/INCREMENT
C
      LTHICK=(WT*VG*FLOAT(LSECT(NSECT))*6.0E+04)/(1.0E+03*A)
C
C
C  CALCULATE MMD AND WEIGHT COLLECTED FOR EACH INCREMENT
C
      ZTM=0.
      DO 2901 J=1,NS
      ZTM=ZTM+WS(J)
      CZA=ZTM/WT
      IF(CZA-0.5)2901,2901,2902
 2901 CONTINUE
 2902 CZB=(ZTM-WS(J))/WT
      TL1=CZA-CZB
      TL2=0.50-CZB
      KJ=J-1
      IF(KJ)2910,2910,2911
 2910 ZMD=DIAM(J)
      GO TO 2912
 2911 ZMD=DIAM(KJ)+(TL2/TL1)*(DIAM(J)-DIAM(KJ))
 2912 CONTINUE
      IF(NVI.EQ.2) ERAVG = SERAVG
      CALL PRTINC
 3000 CONTINUE
C
      ETC=(ZWT/DL)*100.
      IF(NVI.EQ.2) GO TO 1620
      DIFF=ETC-ETAO
      DIFF=ABS(DIFF)
      IF(DIFF-0.05)60,300,300
  300 CONTINUE
      WRITE(NPRNT,8656) ETAO,ETC
 8656 FORMAT(/' EST. EFFICIENCY =',F6.2,5X,'UNCORRECTED COMPUTED EFFICIE
     1NCY =',F6.2)
      IF(ITER.EQ.NITER) GO TO 60
      ETAO=ETC
      GO TO 305
   60 CONTINUE
      GO TO 1621
 1620 CONTINUE
      WRITE(NPRNT,1622) ETAO,ETC
 1622 FORMAT(/' DESIGN EFFICIENCY =',F6.2,5X,'UNCORRECTED COMPUTED EFFIC
     1IENCY =',F6.2)
 1621 CONTINUE
      ATOTAL=0.
      VG=0.
      DO 4985 I=1,NUMSEC
      ATOTAL=ATOTAL+AS(I)*9.3E-02
      VG=VG+(VGS(I)*4.73E-04)
 4985 CONTINUE
      VG=VG/FLOAT(NUMSEC)
      CALL PRTCHG
      CALL ADJUST
      GO TO 4000
 9999 STOP 11111
      END
PROG > 4K
```

```
      SUBROUTINE PRTINP
      REAL LINCS,NWS
      INTEGER VISKIP,VISAME
      DIMENSION IBLNK(21)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,FPSO,PT,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NEST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP
      DATA IBLNK/21*' '/
      IF(LK) 111,111,160
  111 CONTINUE
      WRITE(NPRNT,5850)
 5850 FORMAT(40X,'*************************************')
      WRITE(NPRNT,5851)
 5851 FORMAT(40X,'*',35X,'*')
      WRITE(NPRNT,5852)
 5852 FORMAT(40X,'*',9X,'E.P.A. ESP MODEL',10X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5853)
 5853 FORMAT(40X,'*',4X,'I.E.R.L.-R.T.P. AND SO.R.I.',4X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5854)
 5854 FORMAT(40X,'*',7X,'REVISION I,JAN. 1, 1978',5X,'*')
      WRITE(NPRNT,5851)
      WRITE(NPRNT,5850)
      NDSET=NDSET+1
      DLB=DL/2.29E-03
      PLB=PL/0.305
      RHOCGS=100.*RHO
      NCARD=0
      WRITE(NPRNT,2000) NDSET
 2000 FORMAT(//'  PRINTOUT OF INPUT DATA FOR DATA SET NUMBER ',I2//)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
 2001 FORMAT(//'  DATA ON CARD NUMBER ',I3//)
      WRITE(NPRNT,1000) NENDPT,NDATA
 1000 FORMAT('  NENDPT = ',I2,2X,' NDATA = ',I2)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1001) ITL
 1001 FORMAT(2X,40A2)
      GO TO(6000,6001,6002,6002),NDATA
 6000 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1002) NEST,NDIST,NVI,NX,NY,NITER,NCALC,NRAPD,NEFF,
     1NTEMP,NONID
 1002 FORMAT('  NEST = ',I2,2X,'NDIST = ',I2,2X,'NVI = ',I2,2X,'NX = '
     1,I2,2X,'NY = ',I2,2X,'NITER = ',I2,2X,'NCALC = ',I2,2X,'NRAPD = ',
     2I2,2X,'NEFF = ',I2,2X,'NTEMP = ',I2,2X,'NONID = ',I2)
      IF(NCALC.NE.0) GO TO 1003
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1004) NN,NUMINC
 1004 FORMAT('  NN = ',I2,2X,'NUMINC = ',I2)
 1003 CONTINUE
      IF(NVI.EQ.1) GO TO 1005
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1006) IFINAL,JI1,JI2,VISKIP,VISAME
 1006 FORMAT('  IFINAL = ',I2,2X,'JI1 = ',I2,2X,'JI2 = ',I2,2X,'VISKIP =
     1',I2,2X,'VISAME = ',I2)
 1005 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1007) DLB,PLB,ETAO,DD,EPS
 1007 FORMAT('  DL = ',F8.5,' GRN/ACF',2X,'PL = ',F8.4,' FT',2X,'ETAO =
     1',F8.5,' %',2X,'DD = ',F8.2,' KG/M**3',2X,'EPS = ',1PE10.3/)
      WRITE(NPRNT,1008) VRATIO,US,FPATH,EHD,RHOCGS
 1008 FORMAT('  VRATIO = ',F8.4,2X,'US = ',F8.6,' M**2/V-SEC',2X,'FPATH
     1= ',F8.4,2X,'EHD = ',F8.0,' V/M',2X,'RHOCGS = ',1PE9.2,' OHM-CM')
      IF(NRAPD.EQ.1) GO TO 1009
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1010) (I,ARD50(I),I,ARSIGM(I),I=2,NRAPD)
 1010 FORMAT('  ARD50(',I2,') = ',F4.1,' UM',2X,'ARSIGM(',I2,') = ',F4.1
     1/)
 1009 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      DO 1011 I=1,NONID
      IF(I.EQ.7) NCARD=NCARD+1
      IF(I.EQ.7) WRITE(NPRNT,2001) NCARD
      IF(I.EQ.13) NCARD=NCARD+1
      IF(I.EQ.13) WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,6570) I,ASNUCK(I),I,AZIGGY(I),I,AZNUMS(I)
 6570 FORMAT('  ASNUCK(',I2,') = ',F4.2,2X,'AZIGGY(',I2,') = ',F4.2,2X,'
     1AZNUMS(',I2,') = ',F4.1/)
 1011 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      NDCARD=2
      IF(NENDPT.LE.10) NDCARD=1
      IF(NENDPT.GT.20) NDCARD=3
      GO TO(1012,1013,1014),NDCARD
 1012 CONTINUE
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=1,NENDPT)
 1015 FORMAT(5(1X,A1,'ENDPT(',I2,') = ',F8.3,' UM',1X)/)
      GO TO 1016
 1013 CONTINUE
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=1,10)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=11,NENDPT)
      GO TO 1016
 1014 CONTINUE
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=1,10)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=11,20)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1015) (IBLNK(I),I,ENDPT(I),I=21,NENDPT)
 1016 CONTINUE
 6001 CONTINUE
      IF(NDIST.EQ.1) GO TO 1017
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1018) D50,SIGMAP
 1018 FORMAT('  D50 = ',F8.4,' UM',2X,'SIGMAP = ',F8.4)
 1017 CONTINUE
      IF(NDIST.EQ.2) GO TO 1019
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      GO TO(1020,1021,1022),NDCARD
 1020 CONTINUE
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=1,NENDPT)
 1023 FORMAT(5(1X,A1,'PRCU(',I2,') = ',F8.4,' %',1X)/)
      GO TO 1024
 1021 CONTINUE
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=1,10)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=11,NENDPT)
      GO TO 1024
 1022 CONTINUE
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=1,10)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=11,20)
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1023) (IBLNK(I),I,PRCU(I),I=21,NENDPT)
 1024 CONTINUE
 1019 CONTINUE
      IF(NDATA.GT.1) GO TO 5000
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      IF(NUMSEC.GT.5) GO TO 1026
      WRITE(NPRNT,1025) NUMSEC,(IBLNK(I),I,LSECT(I),I=1,NUMSEC)
 1025 FORMAT('  NUMSEC = ',I2,2X,5(1X,A1,'LSECT(',I2,') = ',I2))
      GO TO 1027
 1026 CONTINUE
      WRITE(NPRNT,1025) NUMSEC,(IBLNK(I),I,LSECT(I),I=1,5)
      WRITE(NPRNT,8570) (IBLNK(I),I,LSECT(I),I=6,NUMSEC)
 8570 FORMAT(/5(1X,A1,'LSECT(',I2,') = ',I2))
 1027 CONTINUE
      DO 1028 I=1,NUMSEC
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1029) I,AS(I),I,VOS(I),I,TCS(I),I,WLS(I)
 1029 FORMAT('  AS(',I2,') = ',1PE11.4,' FT**2',2X,'VOS(',I2,') = ',1PE1
     11.4,' V',2X,'TCS(',I2,') = ',1PE11.4,' A',2X,'WLS(',I2,') = ',1PE1
     21.4,' FT'/)
      WRITE(NPRNT,1030) I,ACS(I),I,BS(I),I,NWS(I)
 1030 FORMAT('  ACS(',I2,') = ',1PE11.4,' IN',2X,'BS(',I2,') = ',1PE11.4
     1,' IN',2X,'NWS(',I2,') = ',1PE11.4)
```

```
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1031) I,SYS(I),I,VGS(I),I,VGASS(I),I,TEMPS(I)
 1031 FORMAT('  SYS(',I2,') = ',1PE11.4,' IN',2X,'VGS(',I2,') = ',1PE11.
     14,' FT**3/MIN',2X,'VGASS(',I2,') = ',1PE11.4,' FT/SEC',2X,'TEMPS('
     2,I2,') = ',1PE11.4,' F'/)
      WRITE(NPRNT,1032) I,PS(I),I,VISS(I),I,LINCS(I)
 1032 FORMAT('  PS(',I2,') = ',1PE11.4,' ATM',2X,'VISS(',I2,') = ',1PE11
     1.4,' KG/M-SEC',2X,'LINCS(',I2,') = ',1PE11.4,' FT')
      IF(NVI.EQ.1) GO TO 1028
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      WRITE(NPRNT,1033) I,RFS(I),I,START1(I),I,START2(I)
 1033 FORMAT('  RFS(',I2,') = ',1PE11.4,2X,'START1(',I2,') = ',1PE11.4,'
     1 A/M**2',2X,'START2(',I2,') = ',1PE11,4,' A/M**2'/)
      WRITE(NPRNT,1034) I,START3(I),I,VSTAR(I)
 1034 FORMAT('  START3(',I2,') = ',1PE11.4,' A/M**2',2X,'VSTAR(',I2,') =
     1 ',1PE11.4,' V')
 1028 CONTINUE
      GO TO 5000
 6002 CONTINUE
      NCARD=NCARD+1
      WRITE(NPRNT,2001) NCARD
      DO 1035 I=1,NUMSEC
      IF(I.EQ.4) NCARD=NCARD+1
      IF(I.EQ.4) WRITE(NPRNT,2001) NCARD
      IF(I.EQ.7) NCARD=NCARD+1
      IF(I.EQ.7) WRITE(NPRNT,2001) NCARD
      IF(I.EQ.10) NCARD=NCARD+1
      IF(I.EQ.10) WRITE(NPRNT,2001) NCARD
      IF(NDATA.EQ.4) GO TO 1036
      WRITE(NPRNT,1037) I,VGS(I),I,VGASS(I)
 1037 FORMAT('  VGS(',I2,') = ',1PE11.4,' FT**3/MIN',2X,'VGASS(',I2,') =
     1 ',1PE11.4,' FT/SEC'/)
      GO TO 1035
 1036 CONTINUE
      WRITE(NPRNT,1038) I,VOS(I),I,TCS(I)
 1038 FORMAT('  VOS(',I2,') = ',1PE11.4,' V',2X,'TCS(',I2,') = ',1PE11.4
     1,' A'/)
 1035 CONTINUE
 5000 CONTINUE
      WRITE(NPRNT,1039)
 1039 FORMAT(1H1)
  160 CONTINUE
      RETURN
      END
      SUBROUTINE SPCHG1 (SW,ROVRI,OROVRI,XS,ETAPF,DW,QSAT,XNO,W,LSECT,
     1TC,VG,ETAO,FID,AFID,AVGFID,XCD,U,UEQ,I,NSECT,LINC,PL,CD,E,ERAVG,
     2NS,XPI)
      REAL LINC
      DIMENSION DW(45),QSAT(20),XNO(20),LSECT(10)
      IF(I.NE.1) GO TO 1286
      SW = 0.0
      ROVRI=10.
      OROVRI=20.0
C
C   COMPUTE VALUE OF EXPONENT IN DEUTSCH EQUATION FOR THE STATED EFF.
C
      XS=ALOG(100./(100.-ETAO))
C
 1286 CONTINUE
C
C   COMPUTE EFFICIENCY PER LENGTH INCREMENT
C
      ETAPF = 1.-EXP(-LINC*XS/PL)
C
C   COMPUTE AMOUNT OF MATERIAL REMOVED PER INCR.ON A TOTAL WEIGHT BASIS
C
      DW(I) = (W - SW) * ETAPF
      SW = SW + DW(I)
      FID=CD/(E*U*ERAVG)
      SUM=0.0
      DO 1300 L=1,NS
 1300 SUM=SUM+QSAT(L)*XNO(L)
      ZC=200.*(DW(I)/W)*(FLOAT(LSECT(NSECT))/TC)*VG*SUM
      ROVRI=ZC+1.0
      AFID=FID/ROVRI
      AVGFID=AFID*1.E-06
      XCD=CD*100000.
C
C   COMPUTE EFFECTIVE MOBILITY
C
      UEQ=U/ROVRI
C
      XPI=ETAPF*100.
      RETURN
      END
      SUBROUTINE SPCHG2 (NS,XNO,VIS,RAD,LINC,E,U,ERAVG,DNSION,
     1DELTNP,SUMMOB,PNUM,RHOP,TCHRG,PMOB,TDNSP,RDNSI,AFID,UEQ,AVGFID,
     2RIOVR,I,XS,ETAO,PL,ETAPF,CCF,XPI,OLDQ,Q,II,NSECT)
      REAL LINC
      DIMENSION XNO(20),RAD(20),CCF(20),OLDQ(20),Q(20)
      COMMON/BLK7/XDC(45,20)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK17/NREAD,NPRNT
      IF(I.NE.1) GO TO 1286
C
C   COMPUTE VALUE OF EXPONENT IN DEUTSCH EQUATION FOR THE DESIGN EFF.
C
      XS=ALOG(100./(100.-ETAO))
C
 1286 CONTINUE
C
C   COMPUTE EFFICIENCY PER LENGTH INCREMENT
C
      ETAPF = 1.-EXP(-LINC*XS/PL)
C
      DELTNP=0.
      SUMMOB=0.
      PNUM=0.
      RHOP=0.
      DO 1 J=1,NS
      TCHRG=XNO(J)*XDC(I,J)
      RHOP=RHOP+TCHRG
      SUMMOB=SUMMOB+(TCHRG*CCF(J))/(6.*3.14159*VIS*RAD(J))
      PNUM=PNUM+XNO(J)
      DIFF=XDC(I,J)
      IF((II.NE.1).OR.(I.NE.1)) DIFF=Q(J)-OLDQ(J)
      DELTNP=DELTNP+XNO(J)*DIFF
    1 CONTINUE
      PMOB=SUMMOB/PNUM
      TDNSP=RHOP/1.6E-19
      DNSION=CHFID(II)
      DELTNP=DELTNP/1.6E-19
      RDNSI=DNSION-DELTNP
      IF(RDNSI.GT.0.) GO TO 10
      PIR=DELTNP/DNSION
      RDNSI=0.
      WRITE(NPRNT,11) PIR,I,II
   11 FORMAT(1X,' A FACTOR OF ',F8.3,' MORE IONS NEEDED IN INCREMENT ',I
     12,', INTERVAL ',I2,' TO MEET CHARGING RATE')
   10 CONTINUE
      AFID=RDNSI
      AVGFID=AFID*1.E-06
      UEQ=(U*AFID*E+PMOB*RHOP)/(AFID*E+RHOP)
      RIOVR=(AFID*E)/(AFID*E+RHOP)
      XPI=ETAPF*100.
      RETURN
      END
```

```
        SUBROUTINE CMAN (VW,NX,NY,SX,SY,PI,AC,NWIRE)
C     COOPERMAN SERIES DETERMINATION FOR VOLTAGE WIRE TO PLATE
C     FOR SUBROUTINE EFIELD
        REAL NUM,M,NWIRE
        COMMON/BLK13/VCOOP(15,15)
        NX1=NX-1
        NY1=NY-1
        AX=SX/NX1
        AY=SY/NY1
        DO 402 I=1,NX
        DO 430 J=1,NY
        X=(I-1)*AX
        Y=(J-1)*AY
        IF(X.EQ.0.0.AND.Y.EQ.0.0) GO TO 440
        GO TO 450
  440   VCOOP(I,J)=VW
        GO TO 430
  450   CONTINUE
        M=-NWIRE
        NUM=0.0
        DENOM=0.0
  490   E1=PI*(Y-(2.*M*SY))/(2.*SX)
        F1=PI*X/(2.*SX)
        G1=PI*M*SY/SX
        H1=PI*AC/(2.*SX)
        E2=(EXP(E1)+EXP(-E1))/2.
        F2=COS(F1)
        G2=(EXP(G1)+EXP(-G1))/2.
        H2=COS(H1)
        TT=(E2-F2)/(E2+F2)
        TB=(G2-H2)/(G2+H2)
        F=ALOG(TT)
        G=ALOG(TB)
        NUM=NUM+F
        DENOM=DENOM+G
        IF(M.LT.NWIRE) GO TO 408
        GO TO 410
  408   M=M+1.0
        GO TO 490
  410   VCOOP(I,J)=VW*NUM/DENOM
  430   CONTINUE
  402   CONTINUE
        RETURN
        END
```

```
      SUBROUTINE EFLD1 (UEQ,CD,AC,VO,SX,SY,NX,NY,TDK,P,AEPLT,VERGE,
     1CVERGE)
C  EVALUATION OF FIELDS, SPACE CHARGE DENSITY, POTENTIAL , AND
C  CURRENT DENSITY FOR A WIRE-PLATE PRECIPITATOR
      REAL MAXJ,MINJ,MOBILT(15,15)
      DIMENSION RHO(15,15),EX(15,15),OLDRO(15,15),OLDV(15,15),
     1CDNSTY(15,15),V(15,15),EY(15,15)
      COMMON/BLK13/VCOOP(15,15)
      COMMON/BLK17/NREAD,NPRNT
      DATA RHO/225*0./,V/225*0./,EX/225*0./,EY/225*0./,OLDRO/225*0./,
     1OLDV/225*0./,CDNSTY/225*0./,MOBILT/225*0./
      VO=-1.*VO
      PI=3.1416
      EPSO=8.854E-12
      RO = AC
      ROC = 100.0*RO
      RF = 1.0
      RELD = (293.0/TDK)*(P/1.0)
      EORO = ROC*RF*(30.0*RELD + 9.0*SQRT(RELD/ROC))*1.0E03
C
C   COMPUTE INITIAL ESTIMATE OF SPACE CHARGE DENSITY AT WIRE
C
      VERGE=(-2.*CD*(1.01 + 0.99)*SY)/(2.*PI*UEQ*EORO)
C
      QZERO=VERGE
      DO 550 I=1,NX
      DO 550 J=1,NY
      MOBILT(I,J)=UEQ
  550 CONTINUE
      MAXJ=CD*1.01
      MINJ=CD*0.99
      NX1=NX-1
      NY1=NY-1
      AX=SX/NX1
      AY=SY/NY1
      AXS=AX*AX
      AYS=AY*AY
      ASP=(AXS*AYS)/EPSO
      ASS=1./(2.*(AXS+AYS))
      Z=0.
      DO 4615 I=1,NX
      DO 4615 J=1,NY
 4615 V(I,J)=VCOOP(I,J)
    1 Z=Z+1.
      IZ=Z
      IF(Z.EQ.25) WRITE(NPRNT,1865)
 1865 FORMAT(1X,' CONVERGENCE ON CURRENT DENSITY CAN NOT BE OBTAINED IN
     125 ITERATIONS')
      IF(Z.EQ.25.) GO TO 700
      LL=0
  300 LL=LL+1
      RHO(1,1)=QZERO
      EX(1,1)=0.0
      EY(1,1)=0.0
      DO 201 I=2,NX
      EY(I,1)=0.
      EX(I,1)=(V(I-1,1)-V(I,1))/AX
      Q1=2.*MOBILT(I,1)
      Q2=Q1*AX
      Q3=Q1*AY
      Q4=Q2*AY
      Q5=-EPSO*EX(I,1)*(Q3-AY*MOBILT(I-1,1))
      Q6=Q5*Q5
      Q7=Q1*Q4*EPSO*AY*EX(I,1)*RHO(I-1,1)
      Q8=-SQRT(Q6+Q7)
      RHO(I,1)=(Q5+Q8)/Q4
  201 CONTINUE
      DO 203 J=2,NY
      EX(1,J)=0.
      EY(1,J)=(V(1,J-1)-V(1,J))/AY
      P1=2.*MOBILT(1,J)
      P2=P1*AX
      P3=P1*AY
      P4=P2*AY
      P5=-EPSO*EY(1,J)*(P2-AX*MOBILT(1,J-1))
      P6=P5*P5
      P7=P1*P4*EPSO*AX*EY(1,J)*RHO(1,J-1)
      P8=-SQRT(P6+P7)
      RHO(1,J)=(P5+P8)/P4
  203 CONTINUE
      DO 202 I=2,NX
      EY(I,NY)=0.
      EX(I,NY)=(V(I-1,NY)-V(I,NY))/AX
      R1=2.*MOBILT(I,NY)
      R2=R1*AX
      R3=R1*AY
      R4=R2*AY
      R5=-EPSO*EX(I,NY)*(R3-AY*MOBILT(I-1,NY))
      R6=R5*R5
      R7=R1*R4*EPSO*AY*EX(I,NY)*RHO(I-1,NY)
      R8=-SQRT(R6+R7)
      RHO(I,NY)=(R5+R8)/R4
  202 CONTINUE
      DO 307 I=2,NX
      DO 307 J=2,NY1
  313 EX(I,J)=(-1.)*(V(I,J)-V(I-1,J))/AX
      EY(I,J)=(-1.)*(V(I,J)-V(I,J-1))/AY
      D1=2.*MOBILT(I,J)
      D2=D1*AX
      D3=D1*AY
      D4=D2*AY
      D5=-EPSO*(EX(I,J)*(D3-AY*MOBILT(I-1,J))+EY(I,J)*(D2-AX*MOBILT(I,J-
     11)))
      D6=D5*D5
      D7=D1*D4*EPSO*(AY*EX(I,J)*RHO(I-1,J)+AX*EY(I,J)*RHO(I,J-1))
      D8=-SQRT(D6+D7)
      RHO(I,J)=(D5+D8)/D4
  307 CONTINUE
      DO 301 I=1,NX1
      DO 301 J=1,NY
      OLDV(I,J)=V(I,J)
      OLDRO(I,J)=RHO(I,J)
      IF(I.EQ.1.AND.J.EQ.1) GO TO 301
      IF(I.EQ.1.AND.J.NE.1) GO TO 304
      IF(I.NE.1.AND.J.EQ.1) GO TO 305
      IF(J.EQ.NY) GO TO 600
      GO TO 306
  600 V(I,NY)=ASS*(AYS*(V(I-1,NY)+V(I+1,NY))+2.*AXS*V(I,NY-1)+ASP*RHO(I,
     1NY))
      GO TO 301
  304 IF(I.EQ.1.AND.J.EQ.NY)  GO TO 350
      V(1,J)=ASS*(2.*AYS*V(2,J)+AXS*(V(1,J+1)+V(1,J-1))+ASP*RHO(1,J))
      GO TO 301
  350 V(1,NY)=ASS*(2.*AYS*V(2,NY)+2.*AXS*V(1,NY-1)+ASP*RHO(1,NY))
      GO TO 301
  305 V(I,1)=ASS*(AYS*(V(I+1,1)+V(I-1,1))+2.*AXS*V(I,2)+ASP*RHO(I,1))
      GO TO 301
  306 V(I,J)=ASS*(AYS*(V(I+1,J)+V(I-1,J))+AXS*(V(I,J-1)+V(I,J+1))+ASP*RH
     1O(I,J))
  301 CONTINUE
      IF(LL.EQ.2000) WRITE(NPRNT,1866)
 1866 FORMAT(1X,' CONVERGENCE ON POTENTIAL GRID CAN NOT BE OBTAINED IN 2
     1000 ITERATIONS')
      IF(LL.EQ.2000) GO TO 700
      DO 320 I=1,NX1
      DO 320 J=1,NY1
      IF(ABS(V(I,J)-OLDV(I,J)).LT.1.) GO TO 320
      GO TO 300
  320 CONTINUE
      CONSTY(NX,1)=EX(NX,1)*MOBILT(NX,1)*RHO(NX,1)
      ACONTY=CONSTY(NX,1)
  950 DO 900 J=2,NY
      CONSTY(NX,J)=EX(NX,J)*MOBILT(NX,J)*RHO(NX,J)
      ACONTY=ACONTY+CONSTY(NX,J)
  900 CONTINUE
      ACONTY=ACONTY/NY
      IF(ACONTY.GT.MAXJ) GO TO 910
      IF(ACONTY.LT.MINJ) GO TO 920
      GO TO 980
 910  QZERO=MINJ/ACONTY*QZERO
      GO TO 1
 920  QZERO=MAXJ/ACONTY*QZERO
      GO TO 1
  980 EPLT=EX(NX,1)
      DO 1000 J=2,NY
      EPLT=EPLT+EX(NX,J)
 1000 CONTINUE
      AEPLT=EPLT/NY
 700  CONTINUE
      CVERGE=QZERO
      VO=-1.*VO
      RETURN
      END
PROG > 4K
```

```
      SUBROUTINE EFLD2 (UEQ,AC,VO,SX,SY,NX,NY,AEPLT,TDK,P,RF,
     1START,DSTART,CSTART,IFINAL,VSTART,VW,ACDNTY,NWIRE,NEC,ERD,JI1,JI2)
C  EVALUATION OF FIELDS, SPACE CHARGE DENSITY, POTENTIAL , AND
C  CURRENT DENSITY FOR A WIRE-PLATE PRECIPITATOR
      REAL MAXJ,MINJ,MOBILT(15,15),NWIRE,MAXS
      DIMENSION RHO(15,15),EX(15,15),OLDRO(15,15),OLDV(15,15),
     1CONSTY(15,15),V(15,15),EY(15,15),EAVGS(30),CHFIDS(30),ECOLLS(30)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK9/ECOLL(30)
      COMMON/BLK13/VCOOP(15,15)
      COMMON/BLK17/NREAD,NPRNT
      DATA RHO/225*0./,V/225*0./,EX/225*0./,EY/225*0./,OLDRO/225*0./,
     1OLDV/225*0./,CONSTY/225*0./,MOBILT/225*0./
      IVCK=0
      VO=-1.*VO
      VW=-1.*VSTART
      RO=AC
      RELD=(293./TDK)*(P/1.)
      ROC=100.*RO
      EORO=ROC*RF*(30.*RELD+9.*SQRT(RELD/ROC))*1.E+03
      DO 550 I=1,NX
      DO 550 J=1,NY
      MOBILT(I,J)=UEQ
  550 CONTINUE
      PI=3.1416
      EPSO=8.854E-12
      SSTART=START
      MINJ=0.
      MAXS=0.
      NX1=NX-1
      NY1=NY-1
      AX=SX/NX1
      AY=SY/NY1
      AXS=AX*AX
      AYS=AY*AY
      ASP=(AXS*AYS)/EPSO
      ASS=1./(2.*(AXS+AYS))
      DO 1001 II=1,IFINAL
      IF(II.EQ.JI1) START=DSTART
      IF(II.GE.JI2) START=CSTART
      MAXS=MAXS+START
 1526 CONTINUE
      MAXJ=MAXS*1.01
      MINJ=MAXS*.99
      QZERO=-(2.*(MAXJ+MINJ)*SY*1.E-03)/(2.*PI*UEQ*ROC*RF*(30.*RELD+9.*
     1SQRT(RELD/ROC)))
      CALL CMAN(VW,NX,NY,SX,SY,PI,AC.NWIRE)
      Z=0
      DO 4615 I=1,NX
      DO 4615 J=1,NY
 4615 V(I,J)=VCOOP(I,J)
    1 Z=Z+1
      IZ=Z
      IF(Z.EQ.25) WRITE(NPRNT,1865)
 1865 FORMAT(1X,' CONVERGENCE ON CURRENT DENSITY CAN NOT BE OBTAINED IN
     125 ITERATIONS')
      IF(Z.EQ.25) GO TO 700
      LL=0
  300 LL=LL+1
      RHO(1,1)=QZERO
      V(1,1)=VW
      EX(1,1)=0.0
      EY(1,1)=0.0
      DO 201 I=2,NX
      EY(I,1)=0.
      EX(I,1)=(V(I-1,1)-V(I,1))/AX
      Q1=2.*MOBILT(I,1)
      Q2=Q1*AX
      Q3=Q1*AY
      Q4=Q2*AY
      Q5=-EPSO*EX(I,1)*(Q3-AY*MOBILT(I-1,1))
      Q6=Q5*Q5
      Q7=Q1*Q4*EPSO*AY*EX(I,1)*RHO(I-1,1)
      Q7=ABS(Q7)
      Q8=-SQRT(Q6+Q7)
      RHO(I,1)=(Q5+Q8)/Q4
  201 CONTINUE
      DO 203 J=2,NY
      EX(1,J)=0.
      EY(1,J)=(V(1,J-1)-V(1,J))/AY
      P1=2.*MOBILT(1,J)
      P2=P1*AX
      P3=P1*AY
      P4=P2*AY
      P5=-EPSO*EY(1,J)*(P2-AX*MOBILT(1,J-1))
      P6=P5*P5
      P7=P1*P4*EPSO*AX*EY(1,J)*RHO(1,J-1)
      P7=ABS(P7)
      P8=-SQRT(P6+P7)
      RHO(1,J)=(P5+P8)/P4
  203 CONTINUE
      DO 202 I=2,NX
      EY(I,NY)=0.
      EX(I,NY)=(V(I-1,NY)-V(I,NY))/AX
      R1=2.*MOBILT(I,NY)
      R2=R1*AX
      R3=R1*AY
      R4=R2*AY
      R5=-EPSO*EX(I,NY)*(R3-AY*MOBILT(I-1,NY))
      R6=R5*R5
      R7=R1*R4*EPSO*AY*EX(I,NY)*RHO(I-1,NY)
      R7=ABS(R7)
      R8=-SQRT(R6+R7)
      RHO(I,NY)=(R5+R8)/R4
  202 CONTINUE
      DO 307 I=2,NX
      DO 307 J=2,NY1
  313 EX(I,J)=(-1.)*(V(I,J)-V(I-1,J))/AX
      EY(I,J)=(-1.)*(V(I,J)-V(I,J-1))/AY
      D1=2.*MOBILT(I,J)
      D2=D1*AX
      D3=D1*AY
      D4=D2*AY
      D5=-EPSO*(EX(I,J)*(D3-AY*MOBILT(I-1,J))+EY(I,J)*(D2-AX*MOBILT(I,J-
     11)))
      D6=D5*D5
      D7=D1*D4*EPSO*(AY*EX(I,J)*RHO(I-1,J)+AX*EY(I,J)*RHO(I,J-1))
      D7=ABS(D7)
      D8=-SQRT(D6+D7)
      RHO(I,J)=(D5+D8)/D4
  307 CONTINUE
      DO 301 I=1,NX1
      DO 301 J=1,NY
      OLDV(I,J)=V(I,J)
      OLDRO(I,J)=RHO(I,J)
      IF(I.EQ.1.AND.J.EQ.1) GO TO 301
      IF(I.EQ.1.AND.J.NE.1) GO TO 304
      IF(I.NE.1.AND.J.EQ.1) GO TO 305
      IF(J.EQ.NY) GO TO 600
      GO TO 306
  600 V(I,NY)=ASS*(AYS*(V(I-1,NY)+V(I+1,NY))+2.*AXS*V(I,NY-1)+ASP*RHO(I,
     1NY))
      GO TO 301
  304 IF(I.EQ.1.AND.J.EQ.NY)  GO TO 350
      V(1,J)=ASS*(2.*AYS*V(2,J)+AXS*(V(1,J+1)+V(1,J-1))+ASP*RHO(1,J))
      GO TO 301
  350 V(1,NY)=ASS*(2.*AYS*V(2,NY)+2.*AXS*V(1,NY-1)+ASP*RHO(1,NY))
      GO TO 301
  305 V(I,1)=ASS*(AYS*(V(I+1,1)+V(I-1,1))+2.*AXS*V(I,2)+ASP*RHO(I,1))
      GO TO 301
  306 V(I,J)=ASS*(AYS*(V(I+1,J)+V(I-1,J))+AXS*(V(I,J-1)+V(I,J+1))+ASP*RH
     1O(I,J))
  301 CONTINUE
      IF(LL.EQ.2000) WRITE(NPRNT,1866)
 1866 FORMAT(1X,' CONVERGENCE ON POTENTIAL GRID CAN NOT BE OBTAINED IN 2
     1000 ITERATIONS')
      IF(LL.EQ.2000) GO TO 700
      DO 320 I=1,NX1
      DO 320 J=1,NY
      IF(ABS(V(I,J)-OLDV(I,J)).LT.1.) GO TO 320
      GO TO 300
  320 CONTINUE
      CDNSTY(NX,1)=EX(NX,1)*MOBILT(NY,1)*RHO(NX,1)
      ACDNTY=CDNSTY(NX,1)
  950 DO 900 J=2,NY
      CDNSTY(NX,J)=EX(NX,J)*MOBILT(NX,J)*RHO(NX,J)
      ACDNTY=ACDNTY+CDNSTY(NX,J)
  900 CONTINUE
      ACDNTY=ACDNTY/NY
      IF(ACDNTY.GT.MAXJ) GO TO 910
      IF(ACDNTY.LT.MINJ) GO TO 920
      GO TO 980
  910 VW=VW+1.*VW*(MAXJ-ACDNTY)/MAXJ
      GO TO 1000
  920 VW=VW+1.*VW*(MINJ-ACDNTY)/MINJ
 1000 CONTINUE
      TEST=ABS(ACDNTY-(MAXJ+MINJ)/2.)
      TEST1=0.01*ACDNTY
      IF(TEST.LT.TEST1) GO TO 980
      GO TO 1
  980 CONTINUE
      EPLT=EX(NX,1)
      DO 1200 J=2,NY
      EPLT=EPLT+EX(NX,J)
 1200 CONTINUE
      AEPLT=EPLT/NY
  700  CONTINUE
      WRITE(NPRNT,8888) VW,ACDNTY,AEPLT
 8888 FORMAT(38X,'VW = ',1PE11.4,2X,'ACDNTY = ',1PE11.4,2X,'AEPLT = ',1P
     1E11.4//)
```

```
      IF(ABS(EX(NX,1)).LT.EBD) GO TO 1480
      WRITE(NPRNT,1481) VW,ACDNTY
 1481 FORMAT(' THE BREAKDOWN FIELD NEAR THE PLATE IS EXCEEDED AT VW =',E
     111.4,1X,'AND ACDNTY =',E11.4)
      GO TO 1525
 1480 CONTINUE
      IF(IVCK.EQ.1) GO TO 1525
      IF(ABS(VW).EQ.ABS(VO)) GO TO 1525
      IF(ABS(VW).GT.ABS(VO)) GO TO 1523
      OLDVW=VW
      OLDCD=ACDNTY
      GO TO 1524
 1523 CONTINUE
      MAXS=ACDNTY-((ACDNTY-OLDCD)/(VW-OLDVW))*(VW-VO)
      VW=OLDVW
      IVCK=1
      GO TO 1526
 1524 CONTINUE
 1001 CONTINUE
 1525 CONTINUE
      IF(NEC.NE.0) GO TO 3000
      K=1
      DO 3001 J=1,NY1
      RSUM=0.
      ESUM=0.
      DO 3002 I=1,NX
      IF(J.EQ.1) GO TO 3005
      ESUM=ESUM+(SQRT(EX(I,J)**2+EY(I,J)**2)+SQRT(EX(I,J+1)**2+
     1EY(I,J+1)**2))/(2.*NX)
      GO TO 3006
 3005 CONTINUE
      ESUM=ESUM+SQRT(EX(I,J+1)**2+EY(I,J+1)**2)/(2.*NX)
      IF(I.EQ.NX) ESUM=ESUM-VO/(2.*SX)
 3006 CONTINUE
      RSUM=RSUM-(RHO(I,J)+RHO(I,J+1))/(2.*1.6E-19*NX)
 3002 CONTINUE
      EAVGS(K)=ESUM
      CHFIDS(K)=RSUM
      K=K+1
 3001 CONTINUE
      NYY=NY1
      DO 3003 L=1,NY1
      EAVG(L)=EAVGS(NYY)
      CHFID(L)=CHFIDS(NYY)
      NYY=NYY-1
 3003 CONTINUE
      KK=1
      M1=NY1+1
      M2=2*NY1
      DO 3004 M=M1,M2
      EAVG(M)=EAVGS(KK)
      CHFID(M)=CHFIDS(KK)
      KK=KK+1
 3004 CONTINUE
 3000 CONTINUE
      LL=1
      DO 3007 NN=1,NY1
      ECOLLS(LL)=-(EX(NX,NN)+EX(NX,NN+1))/2.
      LL=LL+1
 3007 CONTINUE
```

```
      L1=NY1
      DO 3008 L=1,NY1
      ECOLL(L)=ECOLLS(L1)
      L1=L1-1
 3008 CONTINUE
      L2=1
      I1=NY1+1
      I2=2*NY1
      DO 3009 I=I1,I2
      ECOLL(I)=ECOLLS(L2)
      L2=L2+1
 3009 CONTINUE
      VO=-1.*VO
      START=SSTART
      RETURN
      END
PROG > 4K
```

```
      SUBROUTINE CHARGN (ECHARG,SCHARG,NUMINC,CONST,EZERO,V,RSIZE,ECONST
     *,CMKS,RR,FCONST,FACTOR,COEFF,AFID,RATE,H,XI,YI,NN,X,Y)
      H2=H/2.
      Y=YI
      X=XI
      DO 2 I=1,NN
      T1=H*RATE(ECHARG,SCHARG,NUMINC.CONST,EZERO,V,RSIZE,ECONST,CMKS,RR,
     *FCONST,FACTOR,COEFF,AFID,X,Y)
      T2=H*RATE(ECHARG,SCHARG,NUMINC.CONST,EZERO,V,RSIZE,ECONST,CMKS,RR,
     *FCONST,FACTOR,COEFF,AFID,X+H2,Y+T1/2.)
      T3=H*RATE(ECHARG,SCHARG,NUMINC.CONST,EZERO,V,RSIZE,ECONST,CMKS,RR,
     *FCONST,FACTOR,COEFF,AFID,X+H2,Y+T2/2.)
      T4=H*RATE(ECHARG,SCHARG,NUMINC.CONST,EZERO,V,RSIZE,ECONST,CMKS,RR,
     *FCONST,FACTOR,COEFF,AFID,X+H,Y+T3)
      Y=Y+(T1+2.*T2+2.*T3+T4)/6.
      X=X+H
    2 CONTINUE
      RETURN
      END
      FUNCTION RATE (ECHARG,SCHARG,NUMINC,CONST,EZERO,V,RSIZE,ECONST,
     *CMKS,RR,FCONST,FACTOR,COEFF,AFID,NTIME,NUMBER)
      REAL INTGRL,NE,NUMBER,NTIME
      NE=-NUMBER*ECHARG
      IF(NUMBER-SCHARG)7005,7006,7006
 7005 CALL ARCCOS(NUMBER,SCHARG,THZERO)
      IF(THZERO.LE.1.E-05) GO TO 7006
      IF(1.57-THZERO) 7011,7011,7015
 7015 CONTINUE
      GO TO 7007
 7006 THZERO=0.
 7007 DELTAX=(1.57-THZERO)/FLOAT(NUMINC)
      THETA=THZERO-DELTAX
      SUMODD=0.
      DO 7000 J=1,NUMINC,2
      THETA=THETA+DELTAX*2.
      CTHETA=COS(THETA)
      TCONST=CONST*CTHETA
      ECOS=EZERO*CTHETA
      C1=-NE/(CMKS*ECOS)
      CO=TCONST/(2 *ECOS)
      CALL ZERO(C1,CO,RZERO)
      ARG1=-(NUMBER*V*(RZERO-RSIZE)/RZERO+(ECONST-RR*RZERO+FCONST/RZERO*
     1*2)*CTHETA)
      IF(ABS(ARG1).GT.30.0) GO TO 7025
      YVAL=EXP(ARG1)*SIN(THETA)
      GO TO 7026
 7025 YVAL=0.
 7026 CONTINUE
      SUMODD=SUMODD+YVAL
 7000 CONTINUE
      THETA=THZERO
      SUMEVN=0.
      DO 7001 J=2,NUMINC,2
      THETA=THETA+DELTAX*2.
      CTHETA=COS(THETA)
      TCONST=CONST*CTHETA
      ECOS=EZERO*CTHETA
      C1=-NE/(CMKS*ECOS)
      CO=TCONST/(2.*ECOS)
      CALL ZERO(C1,CO,RZERO)
      ARG1=-(NUMBER*V*(RZERO-RSIZE)/RZERO+(ECONST-RR*RZERO+FCONST/RZERO*
     1*2)*CTHETA)
      IF(ABS(ARG1).GT.30.0) GO TO 7027
      YVAL=EXP(ARG1)*SIN(THETA)
      GO TO 7028
 7027 YVAL=0.
 7028 CONTINUE
      IF(J.EQ.NUMINC) GO TO 7001
      SUMEVN=SUMEVN+YVAL
 7001 CONTINUE
      IF(THZERO.EQ.0.) GO TO 7051
 7050 RZERO=RSIZE
      GO TO 7052
 7051 CONTINUE
      CTZERO=COS(THZERO)
      TCONST=CONST*CTZERO
      ECOS=EZERO*CTZERO
      C1=-NE/(CMKS*ECOS)
      CO=TCONST/(2.*ECOS)
      CALL ZERO(C1,C0,RZERO)
 7052 CONTINUE
      ARG2=-(NUMBER*V*(RZERO-RSIZE)/RZERO+(ECONST-RR*RZERO+FCONST/RZERO*
     1*2)*CTZERO)
      IF(ABS(ARG2).GT.30.0) GO TO 7029
      ZVAL=EXP(ARG2)*SIN(THZERO)
      GO TO 7030
 7029 ZVAL=0.
 7030 CONTINUE
      INTGRL=DELTAX/3.*(4.*SUMODD+2.*SUMEVN+ZVAL+YVAL)
      RATE1=INTGRL*FACTOR*AFID
      GO TO 7012
 7011 RATE1=0.
 7012 CONTINUE
      ARG3=-V*NUMBER
      IF(ABS(ARG3).GT.30.0) GO TO 7031
      RATE2=FACTOR*EXP(ARG3)*AFID
      GO TO 7032
 7031 RATE2=0.
 7032 CONTINUE
      IF(NUMBER-SCHARG)7008,7009,7009
 7008 RATE3=COEFF*(1.-NUMBER/SCHARG)**2*AFID
      GO TO 7010
 7009 RATE3=0.
 7010 CONTINUE
      RATE=RATE1+RATE2+RATE3
      RETURN
      END
      SUBROUTINE ARCCOS (A,B,ACOS)
      RATIO=A/B
      T=1.
      SUM=0.
      TERM=RATIO
    1 U=2.*T-1.
      V=2.*T
      W=2.*T+1.
      TERM=TERM/V*U**2/W*RATIO**2
      SUM=SUM+TERM
      T=T+1.
      IF(TERM-5.E-05)3,3,1
    3 ACOS=1.5707963-SUM-RATIO
      RETURN
      END
      SUBROUTINE ZERO (C1,C0,RZERO)
      B=SQRT((27.*C0*C0)/(C1*C1*C1))
      CALL ARCCOS(B,1.,C)
      D=-2.*SQRT(C1/3.)
      RZERO=D*COS((C+6.28318)/3.)
      RETURN
      END
      SUBROUTINE CHGSUM
      REAL LINC,LTHICK,JPART,JION
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK15/NPRINT,NSECT,SLNGTH,A,VO,TC,B,AC,WL,CL,CD,ET,SY,
     1VGAS,P,VIS,W,LINC,XPT,RIOVR,EPLT,AFID,XCD,ZMD,
     2WT,LTHICK,JPART,JION,I,ROVRI
      COMMON/BLK20/SCHARG,CHRFID,TIMEI,TIMEF,V,FACTRE,RSIZE,CNUMBR,J,II,
     1ITER,OLDQF(20),OLDQT(20),SOLDQF(20),SOLDQT(20)
      IF(NVI.EQ.1) GO TO 50
      IF((I.EQ.1).AND.(II.EQ.1)) GO TO 51
      GO TO 52
   51 CONTINUE
      OLDQF(J)=0.
      OLDQT(J)=0.
   52 CONTINUE
      IF(ITER.NE.1) GO TO 53
      IF(II.GT.1) GO TO 50
      SOLDQF(J)=OLDQF(J)
      SOLDQT(J)=OLDQT(J)
   53 CONTINUE
      IF((ITER.GT.1).AND.(II.EQ.1)) GO TO 54
      GO TO 55
   54 CONTINUE
      OLDQF(J)=SOLDQF(J)
      OLDQT(J)=SOLDQT(J)
   55 CONTINUE
   50 CONTINUE
      IF(NVI.EQ.2) GO TO 56
      IF(I.GT.1) GO TO 56
      OLDQF(J)=0.
      OLDQT(J)=0.
   56 CONTINUE
      SATCHG=E*SCHARG
      IF(OLDQF(J).GE.SATCHG) GO TO 1
      CF1=((CHRFID*U*E)/(4.*EPSO))*(TIMEF-TIMEI)
      CF2=1./(1.-OLDQF(J)/SATCHG)
      QF=SATCHG*((CF1+CF2-1.)/(CF1+CF2))
      IF(QF.GT.SATCHG) QF=SATCHG
      GO TO 2
    1 CONTINUE
      QF=OLDQF(J)
    2 CONTINUE
      OLDQF(J)=QF
      ARG=(V*OLDQT(J))/E
      IF(ARG.GT.30.) GO TO 10
      QT=(E/V)*ALOG(((E**2*RSIZE*VAVC*CHRFID)/(4.*EPSO*BC*TDK))*(TIMEF-
     1TIMEI)+EXP(ARG))
      OLDQT(J)=QT
      GO TO 9
   10 CONTINUE
      QT=OLDQT(J)
    9 CONTINUE
      CNUMBR=(QF+QT)/E
      RETURN
      END
      SUBROUTINE PRTINC
      REAL LINC,LTHICK,JPART JION
      COMMON/BLK3/VG,ATOTAL,UD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,F,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK15/NPRINT,NSECT,SLNGTH,A,VO,TC,B,AC,WL,CL,CD,ET,SY,
     1VGAS,P,VIS,W,LINC,XPI,RIOVR,EPLT,AFID,XCD,ZMD,
     2WT,LTHICK,JPART,JION,I,ROVRI
      COMMON/BLK17/NREAD,NPRNT
      IF(NPRINT.NE.1) GO TO 8439
      IF(NSECT.GT.1) GO TO 1585
      WRITE(NPRNT,6550)
 6550 FORMAT(//' INCREMENTAL ANALYSIS OF PRECIPITATOR PERFORMANCE'//)
      WRITE(NPRNT,3010) ITL
 3010 FORMAT('0',40A2/)
 1585 CONTINUE
      NPRINT=0
      WRITE(NPRNT,7820) NSECT,SLNGTH
 7820 FORMAT(/' CALCULATION IS IN SECTION NO. =',I2,' AND THE SECTION LE
     1NGTH IS =',F8.4,' M')
      WRITE(NPRNT,7715) A,VO,TC
 7715 FORMAT(/' COLLECTION AREA =',1PE11.3,' M2',T41,'APPLIED VOLTAGE ='
     1,E11.3,' VOLTS',7X,'TOTAL CURRENT =',E11.3,' AMPS')
      WRITE(NPRNT,7716) B,AC,WL
 7716 FORMAT(' WIRE TO PLATE =',1PE11.3,' M',T41,'CORONA WIRE RADIUS =',
     1E11.3,' M',8X,'CORONA WIRE LENGTH =',E11.3,' M')
      WRITE(NPRNT,7717) CL,CD,ET
 7717 FORMAT(' CURRENT/M =',1PE11.3,' AMP/M',T41,'CURRENT DENSITY =',E11
     1.3,' AMP/M2',6X,'DEPOSIT E FIELD =',E11.3,' VOLT/M')
      WRITE(NPRNT,7718) SY,VG,VGAS
 7718 FORMAT(' 1/2 WIRE TO WIRE =',1PE11.3,' M',T41,'GAS FLOW RATE =',E1
     11.3,' M3/SEC',8X,'GAS VELOCITY =',E11.3,' M/SEC')
      WRITE(NPRNT,7731) TDK,P,VIS
 7731 FORMAT(' TEMPERATURE =',F8.3,' K',T41,'PRESSURE =',F8.3,' ATM',19X
     1,'VISCOSITY =',1PE11.3,' KG/M-SEC')
      WRITE(NPRNT,7732) U,VAVC,TMFP
 7732 FORMAT(' ION MOBILITY =',1PE11.3,' M2/VOLT-SEC',T41,'MEAN THERMAL
     1SPEED =',E11.3,' M/SEC',4X,'PART. PATH PARAM. =',E11.3,' M')
      WRITE(NPRNT,7733) W,LINC,XPI
 7733 FORMAT(' DUST WEIGHT =',1PE11.3,' KG/SEC',T41,'LENGTH INCR. =',0PF
     110.8,' M',15X,'INPUT EFF./INCR. =',F6.2)
      IF(NVI.EQ.1) GO TO 4689
      WRITE(NPRNT,4322)
 4322 FORMAT(//T2,'RIOVR',5X,'ERAVG',8X,'EPLT',8X,'AFID',6X,'CMCD',6X,'M
     1MD',8X,'WEIGHT',4X,'DUST LAYER',3X,'J(PART)',6X,'J(ION)',3X,'INCR.
     2 NO.'/)
      GO TO 4690
 4689 CONTINUE
      WRITE(NPRNT,4333)
 4333 FORMAT(//T2,'ROVRI',5X,'ERAVG',8X,'EPLT',8X,'AFID',6X,'CMCD',6X,'M
     1MD',8X,'WEIGHT',4X,'DUST LAYER',3X,'J(PART)',6X,'J(ION)',3X,'INCR.
     2 NO.'/)
 4690 CONTINUE
 8439 CONTINUE
      IF(NVI.EQ.1) GO TO 4691
      WRITE(NPRNT,4323) RIOVR,ERAVG,EPLT,AFID,XCD,ZMD,WT,LTHICK,
     1JPART,JION,I
 4323 FORMAT(T2,F6.4,1X,1PE11.3,1X,E11.4,1X,E11.4,1X,0PF7.1,1X,1PE10.2,1
     1X,E11.3,1X,E11.3,1X,E10.2,2X,E10.2,6X,I2)
      GO TO 3000
 4691 CONTINUE
      WRITE(NPRNT,4334) ROVRI,ERAVG,EPLT,AFID,XCD,ZMD,WT,LTHICK,
     1JPART,JION,I
 4334 FORMAT(T2,F6.4,1X,1PE11.3,1X,E11.4,1X,E11.4,1X,0PF7.1,1X,1PE10.2,1
     1X,E11.3,1X,E11.3,1X,E10.2,2X,E10.2,6X,I2)
 3000 CONTINUE
      RETURN
      END
      SUBROUTINE PRTCHG
      REAL NWS
      INTEGER VISKIP,VISAME
      DIMENSION YY(20)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK4/NS
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK7/XDC(45,20)
      COMMON/BLK8/EAVG(30),CHFID(30)
      COMMON/BLK14/TMFP,NVI
      COMMON/BLK16/NCALC,NI,VRATIO,NF
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NFST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP
C
C OUTPUT FROM CHARGING ROUTINE
C
      WRITE(NPRNT,9992)
 9992 FORMAT(1H1)
      WRITE(NPRNT,356)
  356 FORMAT(/T3,'CHARGING RATES FOR PARTICLE SIZES FROM SUBROUTINE CHAR
     1GN OR CHGSUM'/)
      IF((NCALC.EQ.1).OR.(NFST.EQ.2)) GO TO 1880
      WRITE(NPRNT,1879)
 1879 FORMAT(/T3,'SRI THEORY USED FOR PARTICLE CHARGING')
      GO TO 1881
 1880 CONTINUE
      WRITE(NPRNT,1882)
 1882 FORMAT(/T3,'SUM OF CLASSICAL FIELD AND DIFFUSIONAL CHARGES USED FO
     1R PARTICLE CHARGING')
 1881 CONTINUE
      WRITE(NPRNT,2500)
 2500 FORMAT(//T2,'INCREMENT NO.',T20,'Q/QSATF FOR INDICATED PARTICLE SI
     1ZES')
      JS=1
      KS=8
 6544 CONTINUE
      IF(KS-NS) 6541,6542,6542
 6542 CONTINUE
      KS=NS
 6541 CONTINUE
      WRITE(NPRNT,357) (DIAM(J),J=JS,KS)
  357 FORMAT(//T4,10(E11.4,2X)//)
      DO 360 I=1,NF
      DO 359 J=JS,KS
      IF(NVI.EQ.1) GO TO 4692
      N = NI/2
      QSATM=(4.*PI*EPSO*(RAD(J)+TMFP)**2)*EAVG(N)*(1.+2.*((EPS-1.)/
     1(EPS+2.))*(RAD(J)/(RAD(J)+TMFP))**3)*VRATIO
      YY(J)=XDC(I,J)/QSATM
      GO TO 359
 4692 CONTINUE
      YY(J)=XDC(I,J)/QSAT(J)
  359 CONTINUE
      WRITE(NPRNT,358) I,(YY(J),J=JS,KS)
  358 FORMAT(T3,I2,T6,10(F7.4,6X))
  360 CONTINUE
      IF(KS.EQ.NS) GO TO 6543
      JS=JS+8
      KS=KS+8
      GO TO 6544
 6543 CONTINUE
      WRITE(NPRNT,9992)
      WRITE(NPRNT,432)
  432 FORMAT(/T5,'CHARGE ACCUMULATED ON PARTICLE SIZES IN EACH INCREMENT
     1'//T3,'INCREMENT',T20,'CHARGE FOR INDICATED PARTICLE SIZES')
      JS=1
      KS=8
 6565 CONTINUE
      IF(KS-NS) 6566,6567,6567
 6567 CONTINUE
      KS=NS
 6566 CONTINUE
      WRITE(NPRNT,425) (DIAM(J),J=JS,KS)
  425 FORMAT(//T8,10(E11.4,3X)//)
      DO 431 I=1,NF
      WRITE(NPRNT,430) I,(XDC(I,J),J=JS,KS)
  430 FORMAT(T3,I2,T6,10(E13.5,1X))
  431 CONTINUE
      IF(KS.EQ.NS) GO TO 6568
      JS=JS+8
      KS=KS+8
      GO TO 6565
 6568 CONTINUE
      RETURN
      END
      SUBROUTINE ADJUST
C           *****************************************
C           *                                       *
C           *  RAPPING REENTRAINMENT PROCEDURE IN   *
C           *                                       *
C           *  THIS SUBROUTINE WAS DEVELOPED UNDER  *
C           *                                       *
C           *  THE SPONSORSHIP OF E.P.R.I. BY SO.R.I.  *
C           *                                       *
C           *****************************************
      DOUBLE PRECISION EFFESR,DLOG,EFFWR
      REAL LINCS
      DIMENSION RPCNT(20),DMDLD(20),WUNCOR(20),RDMDLD(20),CDMDLD(20),
     1PCTOT(20),CPCTOT(20),WSL(20),PXS(20),PRCUNR(21),RPRCU(21),
     2PRCUC(21),EUNCOR(20)
      COMMON/BLK1/DIAM(20),ONO(20),DXS(20),XMV(20),PCNT(20),RAD(20),
     1CCF(20),PRCU(21)
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK4/NS
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,F,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK11/ENDPT(21),NENDPT
      COMMON/BLK12/ARD50(10),ARSIGM(10),ASNUCK(15),AZNUMS(15),AZIGGY(15)
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK18/SCOPEF,CZMDL,CSIGMO,NRUN,SNUCK,ZIGGY,RMMD,RSIGMA
      COMMON/BLK19/LK,DV,NN,NUMINC,NX,NY,NDATA,NFST,NDIST,NITER,IFINAL,
     1JI1,JI2,VISKIP,VISAME,US,FPATH,EBD,NDSET,NWS(10),D50,SIGMAP
      NRUN = 0
      NS1=NS+1
      NUMS1=NUMSEC-1
      CONVF=3.67E+03*(TDK/PS(NUMSEC))
      NRAPDC=0
      X=0.0
      DO 1555 I=1,NS
      EFFESR=DXS(I)/ONO(I)
      IF(EFFESR.GT.0.999999) EFFESR=0.999999
      X=X+EFFESR*PCNT(I)
 1555 CONTINUE
 1713 CONTINUE
      NRAPDC=NRAPDC+1
      IF(NRAPDC.EQ.1) GO TO 6078
      GO TO 6080
 6078 CONTINUE
      ARD50(1)=6.0
      ARSIGM(1)=2.5
      RMMD=6.0
      RSIGMA=2.5
      GO TO 6079
 6080 CONTINUE
      RMMD=ARD50(NRAPDC)
      RSIGMA=ARSIGM(NRAPDC)
 6079 CONTINUE
      CALL LNDIST(RMMD,RSIGMA,RPRCU,RPCNT)
      DO 7575 I=1,NS
      RPCNT(I)=RPCNT(I)*1.E+02
 7575 CONTINUE
      NONCK=0
 1867 CONTINUE
      NONCK=NONCK+1
      SNUCK=ASNUCK(NONCK)
      ZIGGY=AZIGGY(NONCK)
      ZNUMS=AZNUMS(NONCK)
      WRITE(NPRNT,18)
   18 FORMAT(1H1,' PARTICLE SIZE RANGE STATISTICS'/)
      WRITE(NPRNT,1868) NONCK
 1868 FORMAT(/' CORRECTIONS FOR NONIDEALITIES USING SET NO. ',I2,' OF CO
     1RRECTION PARAMETERS'/)
C
C        PRINT DIAM., PERCENT, AND EFFICIENCY FOR EACH SIZE RANG
C
      WRITE(NPRNT,19)
   19 FORMAT(4X,'SIZE',5X,'CCF',2X,'INLET %',1X,'OUTLET %',1X,'COR. OUTL
     1ET %',1X,'NO-RAP EFF.',1X,'NO-RAP W',2X,'NO-RAP P',2X,'COR. EFF.',
     23X,'COR. W',5X,'COR. P')
C
C
      Y=0.0
      DO 2990 I=1,NS
      EFESR=DXS(I)/DNO(I)
      IF (EFESR .GT..999999 ) EFESR = .999999
      XEP=EFESR*100.D0
      IF (XEP .GE. 99.9999  ) XEP = 99.9999
      IF(EFESR.GE.0.99999)WY=XMV(I)*100.
      IF(EFESR.LT.0.99999)WY=(VG/ATOTAL)*100.*ALOG(100./(100.-XEP))
      IF(ZIGGY-0.0)4704,4704,4705
 4704 F1=1.
      GO TO 4706
 4705 CONTINUE
      F1=1.+.766*EFESR*ZIGGY**1.786+.0755*ZIGGY*DLOG(1.D0/(1.D0-EFESR))
 4706 CONTINUE
      IF(SNUCK-0.0)4701,4701,4702
 4701 F2=1.
      GO TO 4703
 4702 F2=DLOG(1.-EFESR)/(ZNUMS*DLOG(SNUCK+(1.-SNUCK)*(1.0-EFESR)**(1./
     1ZNUMS)))
 4703 CONTINUE
      WYS=WY/F2
      WYV=WY/F1
      ZNLFF = F1*F2
      WYSV=WY/ZNLFF
      WUNCOR(I)=WY
      EUNCOR(I)=EFESR*100.
      CALL WADJST(DIAM,I,WYSV,DNO,PXS,ATOTAL,VG,EFESR)
      IF (EFESR .GT..999999 ) EFESR = .999999
      XEP=EFESR*100.D0
      IF (XEP .GE. 99.9999  ) XEP = 99.9999
      IF(EFESR.GE.0.99999)WY=XMV(I)*100.
      IF(EFESR.LT.0.99999)WY=(VG/ATOTAL)*100.*ALOG(100./(100.-XEP))
      PXS(I)=EFESR*DNO(I)
      Y = Y + EFESR * PCNT(I)
 2990 CONTINUE
      IDC=0
      SPO=0.
      SCPO=0.
      IX=0
 1341 CONTINUE
      SCOREF = 0.0
      IDC=IDC+1
      DO 3540 I=1,NS
      IX=IX+1
      EFESR=PXS(I)/ONO(I)
      IF (EFESR .GT..999999 ) EFESR = .999999
      XEP=EFESR*100.D0
      IF (XEP .GE. 99.9999  ) XEP = 99.9999
      IF(EFESR.GE.0.99999)WY=XMV(I)*100.
      IF(EFESR.LT.0.99999)WY=(VG/ATOTAL)*100.*ALOG(100./(100.-XEP))
      XY=PCNT(I)*100.
      PENTR=100.-XEP
      PCTOT(I)=PENTR*PCNT(I)*1.E-02
      IF(IX.GT.1) GO TO 7130
      CLPTLS=0.
      DO 1 IS=1,NUMS1
      CLPTLS=CLPTLS+FLOAT(LSECT(IS))*LINCS(IS)*0.305
    1 CONTINUE
      NYX=0
 1430 CONTINUE
      NYX=NYX+1
      IF(NYX.EQ.2) GO TO 1431
      XEFF=Y
      IF(NEFF.EQ.2) XEFF=X
      EXPONT=ALOG(1./(1.-XEFF))
      XMELS=DL*EXP(-(EXPONT*CLPTLS)/PL)
      XMCLS=XMELS*(1.-EXP(-(EXPONT*FLOAT(LSECT(NUMSEC))*LINCS(NUMSEC)*0.
     1305)/PL))
      XMLLS=XMELS-XMCLS
      XMCLS=XMCLS*CONVF
      IF(NTEMP.EQ.1) RAPLOS=0.155*XMCLS**0.905
      IF(NTEMP.EQ.2) RAPLOS=0.618*XMCLS**0.894
      GO TO 1432
 1431 CONTINUE
      EXPONT=ALOG(1./(1.-Y))
      YMELS=DL*EXP(-(EXPONT*CLPTLS)/PL)
      YMCLS=YMELS*(1.-EXP(-(EXPONT*FLOAT(LSECT(NUMSEC))*LINCS(NUMSEC)*0.
     1305)/PL))
      YMLLS=YMELS-YMCLS
      YMCLS=YMCLS*CONVF
 1432 CONTINUE
      IF(NYX.EQ.1) GO TO 1430
 7130 CONTINUE
      RNS=((RAPLOS/(DD*CONVF))*RPCNT(I)*1.E-02)/((3.14159*DIAM(I)**3)/6.
     1)
      WYSV=WY
      EFFWR=(ONO(I)*(1.-EXP(-(ATOTAL*WYSV)/(100.*VG)))-RNS)/ONO(I)
      CRNP = ONO(I)*(1.-EXP(-(ATOTAL*WYSV)/(100.*VG)))- RNS
      IF(CRNP.LE.0.0) EFFWR = EFESR
      IF(EFFWR.GT..999999) EFFWR=.999999
      COREFF=EFFWR*100.D0
      IF(COREFF.GE.99.9999) COREFF=99.9999
      IF(EFFWR.GE.0.99999) WYP=WYSV
      IF(EFFWR.LT.0.99999) WYP=(VG/ATOTAL)*100.*ALOG(100./(100.-COREFF))
      SCOREF = SCOREF + COREFF*PCNT(I)
      CPENTR=100.-COREFF
      CPCTOT(I)=CPENTR*PCNT(I)*1.E-02
      IF(IDC.NE.1) GO TO 1343
      SPO=SPO+PCTOT(I)
      SCPO=SCPO+CPCTOT(I)
 1343 CONTINUE
      SL=(1.0-EFESR)*ONO(I)
      WSL(I)=SL*(1.33333*3.14159*RAD(I)**3)*DD
      IF(IDC.EQ.1) GO TO 1344
      PCTOT(I)=(PCTOT(I)/SPO)*100.
      CPCTOT(I)=(CPCTOT(I)/SCPO)*100.
      DLD=ALOG10(ENDPT(I+1))-ALOG10(ENDPT(I))
      DMDLD(I)=(PCTOT(I)*YMLLS*CONVF*1.E-02)/DLD
      RDMDLD(I)=(RPCNT(I)*RAPLOS*1.E-02)/DLD
      CDMDLD(I)=DMDLD(I)+RDMDLD(I)
      WRITE(NPRNT,2291) DIAM(I),CCF(I),XY,PCTOT(I),CPCTOT(I),XEP,WY,
     1PENTR,COREFF,WYP,CPENTR
 2291 FORMAT(1X,1PE10.3,1X,0PF6.3,1X,F6.3,2X,F7.4,5X,F7.4,4X,F8.4,3X,F7.
     13,2X,F8.4,3X,F8.4,2X,F7.3,4X,F8.4)
 1344 CONTINUE
 3540 CONTINUE
      IF(IDC.EQ.1) GO TO 1341
C
      Y=Y*100.
      X = X * 100.
      WRITE(NPRNT,2292) ETAO,X
 2292 FORMAT('0',4X,'EFFICIENCY - STATED = ',F5.2,5X,'COMPUTED =' ,F8.4
     $,5X,'CONVERGENCE OBTAINED')
      X=X/100.
      WRITE(NPRNT,3675) Y
 3675 FORMAT(//5X,23HADJUSTED NO-RAP EFF. = ,F8.4)
      WRITE(NPRNT,5802) ZMMDI
 5802 FORMAT(5X,'MMD OF INLET SIZE DISTRIBUTION =',1PE11.3)
      WRITE(NPRNT,5803) SIGMI
 5803 FORMAT(5X,'SIGMAP OF INLET SIZE DISTRIBUTION =',1PE11.3)
      IF(NDIST.EQ.1) WRITE(NPRNT,9250) GFIT
 9250 FORMAT(5X,'LOG-NORMAL GOODNESS OF FIT = ',F6.3)
C
C CALCULATE MMD OF EFFLUENT UNDER NO-RAP CONDITIONS
C
      PRCUNR(1)=0.
      SUMNR=PRCUNR(1)
      DO 1750 I=1,NS
      SUMNR=SUMNR+PCTOT(I)
      PRCUNR(I+1)=SUMNR
 1750 CONTINUE
      CALL LNFIT(PRCUNR,ZMDL,SIGMO,ZGFIT)
 2982 WRITE(NPRNT,2997) ZMDL
 2997 FORMAT(5X,'MMD OF EFFLUENT UNDER NO-RAP CONDITIONS =',1PE11.3)
      WRITE(NPRNT,5801) SIGMO
 5801 FORMAT(5X,'SIGMAP OF EFFLUENT UNDER NO-RAP CONDITIONS =',1PE11.3)
      WRITE(NPRNT,9250) ZGFIT
      COREFW=(VG/ATOTAL)*100.*ALOG(100./(100.-SCOREF))
      WZ=(VG/ATOTAL)*100.*ALOG(100./(100.-Y))
      WRITE(NPRNT,2998) WZ
 2998 FORMAT(5X,'PRECIPITATION RATE PARAMETER UNDER NO-RAP CONDITIONS ='
     1,F7.3//)
      PRCUC(1)=0.
      SUMC=PRCUC(1)
      DO 1751 I=1,NS
      SUMC=SUMC+CPCTOT(I)
      PRCUC(I+1)=SUMC
 1751 CONTINUE
      CALL LNFIT(PRCUC,CZMDL,CSIGMO,CGFIT)
      WRITE(NPRNT,4615) ZIGGY,SNUCK,ZNUMS
 4615  FORMAT(5X,'SIGMAG=',2X,F7.3,2X,'WITH',F7.3,' SNEAKAGE OVER',2X,
     1F7.3,2X,'STAGES')
      WRITE(NPRNT,7900) NTEMP
 7900 FORMAT(5X,'NTEMP =',I2)
      WRITE(NPRNT,7901) RMMD
 7901 FORMAT(5X,'RMMD =',F6.2)
      WRITE(NPRNT,7902) RSIGMA
 7902 FORMAT(5X,'RSIGMA =',F5.2)
      WRITE(NPRNT,5002) SCOREF
 5002  FORMAT(5X,'CORR. EFF. = ',F8.4)
      WRITE(NPRNT,8352) CZMDL
 8352 FORMAT(5X,'CORRECTED MMD OF EFFLUENT =',1PE11.3)
      WRITE(NPRNT,5800) CSIGMO
 5800 FORMAT(5X,'CORRECTED SIGMAP OF EFFLUENT =',1PE11.3)
      WRITE(NPRNT,9250) CGFIT
      WRITE(NPRNT,5003) COREFW
 5003 FORMAT(5X,'CORRECTED PRECIPITATION RATE PARAMETER =',F8.2)
      WRITE(NPRNT,6565)
 6565 FORMAT(1H1,' UNADJUSTED MIGRATION VELOCITIES AND EFFICIENCIES, AND
     1 DISCRETE OUTLET MASS LOADINGS'//)
      WRITE(NPRNT,1980)
 1980 FORMAT(1X,16HIDEAL UNADJUSTED,3X,16HIDEAL UNADJUSTED,7X,6HNO-RAP,1
     10X,12HRAPPING PUFF,6X,15HNO-RAP+RAP PUFF,5X,12HRAPPING PUFF,4X,8HP
     2ARTICLE)
      WRITE(NPRNT,1981)
 1981 FORMAT(1X,17HMIG. VEL.(CM/SEC),4X,13HEFFICIENCY(%),4X,17HDM/DLOGD(
     1MG/DSCM),2X,17HDM/DLOGD(MG/DSCM),2X,17HDM/DLOGD(MG/DSCM),2X,15HDIS
     2TRIBUTION(%),2X,8HDIAM.(M))
      DO 1982 M=1,NS
      WRITE(NPRNT,1983) WUNCOR(M),EUNCOR(M),DMDLD(M),RDMDLD(M),
     1CDMDLD(M),RPCNT(M),DIAM(M)
 1983 FORMAT(1X,1PE10.3,4(10X,1PE10.3),7X,1PE10.3,6X,1PE10.3)
 1982 CONTINUE
      NRUN = NRUN + 1
      CALL PRTSUM
      IF(NONCK.LT.NONID) GO TO 1867
      IF(NRAPDC.LT.NRAPD) GO TO 1713
      RETURN
      END
      SUBROUTINE WADJST (DIAM,I,WY,ONO,PXS,ATOTAL,VG,EFESR)
C               ******************************************
C               *                                        *
C               *  CORRECTION FACTORS IN THIS SUBROUTINE *
C               *                                        *
C               *  ARE BASED ON DATA TAKEN UNDER         *
C               *                                        *
C               *  E.P.R.I. SPONSORSHIP BY SO.R.I.       *
C               *                                        *
C               ******************************************
      DOUBLE PRECISION EFESR
      DIMENSION DIAM(20),ONO(20),PXS(20),CFACT(24),DCHECK(24)
      DATA CFACT/2.43,2.325,2.24,2.17,2.11,2.05,2.00,1.965,1.92,1.885,1.
     185,1.82,1.79,1.76,1.74,1.71,1.685,1.5,1.37,1.27,1.18,1.115,1.05,1.
     200/
      DATA DCHECK/.2E-06,.25E-06,.3E-06,.35E-06,.4E-06,.45E-06,.5E-06,.5
     15E-06,.6E-06,.65E-06,.7E-06,.75E-06,.8E-06,.85E-06,.9E-06,.95E-06,
     21.E-06,1.5E-06,2.E-06,2.5E-06,3.E-06,3.5E-06,4.E-06,4.5E-06/
      IF((DIAM(I).LT.2.0E-07).OR.(DIAM(I).GE.4.5E-06)) GO TO 6
      DO 3 L=1,23
      IF((DIAM(I).GE.DCHECK(L)).AND.(DIAM(I).LE.DCHECK(L+1))) GO TO 4
      GO TO 3
    4 CONTINUE
      WFACT=CFACT(L)-((DIAM(I)-DCHECK(L))/(DCHECK(L+1)-DCHECK(L)))*
     1(CFACT(L)-CFACT(L+1))
      WY=WY*WFACT
      EFESR=1.-EXP(-(ATOTAL*WY)/(100.*VG))
      PXS(I)=EFESR*ONO(I)
      GO TO 5
    3 CONTINUE
    6 CONTINUE
      EFESR=1.-EXP(-(ATOTAL*WY)/(100.*VG))
      PXS(I)=EFESR*ONO(I)
    5 CONTINUE
      RETURN
      END
      SUBROUTINE LNDIST (D50,SIGMAP,PRCU,PCNT)
      DIMENSION Y(100),Z(100),AREA(20),PRCU(21),PCNT(20)
      COMMON/BLK4/NS
      COMMON/BLK11/ENDPT(21),NENDPT
      PI=3.1416
      SIGMAZ=ALOG(SIGMAP)
      N=NS+2
      NINC=100
      ASUM=0.
      K=0
      DO 240 J=1,N
      IF(J.EQ.1)GO TO 230
      IF(J.EQ.(N))GO TO 232
      X2=ALOG(ENDPT(J))
      X1=ALOG(ENDPT(J-1))
      GO TO 233
230   CONTINUE
      X1=ALOG(0.01)
      X2=ALOG(ENDPT(J))
      GO TO 233
232   CONTINUE
      X1=ALOG(ENDPT(J-1))
      X2=ALOG(1000.)
233   CONTINUE
      DX=(X2-X1)/99.
      D=X1
      SGT1=1./(SIGMAZ*(2.*PI)**.5)
      SGT2=2.*SIGMAZ**2
      DO 234 I=1,NINC
      Y(I)=SGT1*EXP(-(D-ALOG(D50))**2/SGT2)
      D=D+DX
234   CONTINUE
      CALL QTFE(DX,Y,Z,NINC)
      ASUM=ASUM+Z(NINC)
      IF(J.LT.N) PRCU(J)=ASUM
      IF((J.EQ.1).OR.(J.EQ.N))GO TO 240
      K=K+1
      AREA(K)=Z(NINC)
240   CONTINUE
      DO 241 I=1,NS
      PCNT(I)=AREA(I)/ASUM
241   CONTINUE
      SUM=0.
      DO 2 I=1,NS
      SUM=SUM+PCNT(I)
2     CONTINUE
      CHECK1 = 1.0 - SUM
      PCNT(NS)=PCNT(NS)+CHECK1
      CHECK2 = 1.0 - PRCU(NENDPT)
      PRCU(NENDPT)=PRCU(NENDPT)+CHECK2
      RETURN
      END
```

```
            SUBROUTINE QTFE (DX,Y,Z,NINC)
            DIMENSION Y(1),Z(1)
            SUM2=0.
            IF(NINC - 1) 4,3,1
      1     DDX=.5*DX
      C
      C     INTEGRATION LOOP
            DO2 I=2,NINC
            SUM1=SUM2
            SUM2=SUM2+DDX*(Y(I)+Y(I-1))
      2     Z(I-1)=SUM1
      3     Z(NINC)=SUM2
      4     RETURN
            END
      SUBROUTINE LNFIT (PRCU,D50,SIGMAP,GFIT)
C     THIS SUBROUTINE FITS CUMPERCENT CURVE TO A LOGNORMAL DISTRIBUTION
      DIMENSION Z(21),Y(21),PRCU(21)
      COMMON/BLK11/ENDPT(21),NENDPT
      NSTAG=0
      J=0
      DO 1 I=1,NENDPT
      IF(PRCU(I).LE.0.0)GO TO 1
      J=J+1
      Z(J)=ALOG(ENDPT(I))
      IF(PRCU(I).GE.99.0) GO TO 4
      IF(PRCU(I).GT.50.)GO TO 3
      XY=PRCU(I)/100.
2     XYY=SQRT(ALOG(1.0/XY**2))
      Y(J)=XYY-((2.515517+0.802853*XYY+0.010328*XYY**2)/(1.0+1.432788*X
     1YY+0.189269*XYY**2+0.001308*XYY**3))
      IF(PRCU(I).GT.50.)GO TO 5
      Y(J)=-Y(J)
      GO TO 5
3     XY=1.0-(PRCU(I)/100.)
      GO TO 2
5     NSTAG=NSTAG+1
1     CONTINUE
C     CALL CURVE FIT ROUTINE
4     CALL CFIT(A,B,GFIT,NSTAG,Z,Y)
C     CALCULATE D50 AND SIGMAP
      D50=EXP(-A/B)
      SIGMAP=EXP(1.0/B)
      RETURN
      END
      SUBROUTINE CFIT (A,B,R,NSTAG,Z,Y)
C     THIS SUBROUTINE FITS A STRAIGHT LINE, Y=A+BX, USING LEAST SQUARES
      DIMENSION Z(21),Y(21)
      XN=0.0
      SUMX=0.0
      SUMY=0.0
      SUMXY=0.0
      SUMXX=0.0
      SUMYY=0.0
      DO 6 I=1,NSTAG
      SUMX=SUMX+Z(I)
      SUMY=SUMY+Y(I)
      SUMXY=SUMXY+Z(I)*Y(I)
      SUMXX=SUMXX+Z(I)**2
      SUMYY=SUMYY+Y(I)**2
      XN=XN+1.0
6     CONTINUE
C     CALCULATE A,B
      B=(XN*SUMXY-SUMX*SUMY)/(XN*SUMXX-SUMX**2)
      A=(SUMXX*SUMY-SUMX*SUMXY)/(XN*SUMXX-SUMX**2)
      R=SQRT(B*((XN*SUMXY-SUMX*SUMY)/(XN*SUMYY-SUMY**2)))
      RETURN
      END
      SUBROUTINE PRTSUM
      PEAL LINCS
      COMMON/BLK2/LSECT(10),LINCS(10),PS(10)
      COMMON/BLK3/VG,ATOTAL,DD,ETAO,DL,PL,RHO
      COMMON/BLK5/ZMMDI,SIGMI,NONID,NRAPD,TDK,NUMSEC,NEFF,NTEMP,GFIT
      COMMON/BLK6/VOL(20),XNO(20),Q(20),WS(20),ITL(40),DW(45),AS(10),
     1VOS(10),TCS(10),WLS(10),ACS(10),BS(10),SYS(10),VGS(10),VGASS(10),
     2TEMPS(10),VISS(10),QSAT(20),U,E,EPSO,PI,ERAVG,BC,TEMP,EPS,VAVC,
     3OLDQ(20),OLDXNO(20),RFS(10),START1(10),START2(10),START3(10),
     4VSTAR(10)
      COMMON/BLK17/NREAD,NPRNT
      COMMON/BLK18/SCOREF,CZMDL,CSIGMO,NRUN,SNUCK,ZIGGY,RMMD,RSIGMA
      SCA=ATOTAL/VG
      VOSUM=0.
      CDSUM=0.
      DO 6571 I=1,NUMSEC
      VOSUM=VOS(I)*FLOAT(LSECT(I))*LINCS(I)*0.305+VOSUM
      CDSUM=(TCS(I)/(AS(I)*9.3E-02))*1.E+05*FLOAT(LSECT(I))*LINCS(I)*
     10.305+CDSUM
 6571 CONTINUF
      AVO=VOSUM/PL
      ACD=CDSUM/PL
      RHOCGS=RHO*100.
      WRITE(NPRNT,1994)
 1994 FORMAT(1H1)
      WRITF(NPRNT,9520)
 9520 FORMAT(9X,'*******************************************************
     1*************************************************************')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
 1060 FORMAT(9X,'*',114X,'*')
      WRITE(NPRNT,9500)
 9500 FORMAT(9X,'*',39X,'SUMMARY TABLE OF ESP OPERATING',45X,'*')
      WRITE(NPRNT,9501)
 9501 FORMAT(9X,'*',41X,'PARAMETERS AND PERFORMANCE',47X,'*')
      WRITE(NPRNT,1060)
      WRITF(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITF(NPRNT,1060)
      WRITF(NPRNT,9502) NRUN
 9502 FORMAT(9X,'*',46X,'DATA SET NUMBER ',I3,49X,'*')
      WRITE(NPRNT,1060)
      WRITF(NPRNT,1060)
      WRITF(NPRNT,9503) SCOREF,SCA
 9503 FORMAT(9X,'*',12X,'ESP PERFORMANCE:',5X,'EFFICIENCY = ',F8.4,' %',
     15X,'SCA = ',1PE10.3,' M**2/(M**3/SEC)',21X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9504) AVO
 9504 FORMAT(9X,'*',12X,'ELECTRICAL CONDITIONS:',5X,'AVG. APPLIED VOLTAG
     1E = ',1PE10.3,' V',40X,'*')
      WRITF(NPPNT,1060)
      WRITE(NPRNT,9505) ACD
 9505 FORMAT(9X,'*',39X,'AVG. CURRENT DENSITY = ',F7.2,' NA/CM**2',36X,'
     1*')
      WRITF(NPRNT,1060)
      WRITE(NPRNT,9506) RHOCGS
 9506 FORMAT(9X,'*',39X,'RESISTIVITY = ',1PE10.3,' OHM-CM',44X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9507) ZMMDI,SIGMI
 9507 FORMAT(9X,'*',12X,'SIZE DISTRIRUTIONS:',5X,'INLET MMD = ',1PE10.3,
     1' UM',5X,'INLET SIGMAP = ',1PE10.3,23X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9508) CZMDL,CSIGMO
 9508 FORMAT(9X,'*',36X,'OUTLET MMD = ',1PE10.3,' UM',5X,'OUTLET SIGMAP
     1= ',1PE10.3,21X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9509) SNUCK,ZIGGY
 9509 FORMAT(9X,'*',12X,'NONIDEAL PARAMETERS:',5X,'GAS SNEAKAGE FRACTION
     1 = ',F4.2,' /SECTION',5X,'GAS VELOCITY SIGMAG = ',F4.2,9X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9510) RMMD,RSIGMA
 9510 FORMAT(9X,'*',37X,'RAPPING MMD = ',1PE10.3,' UM',5X,'RAPPING SIGMA
     1P = ',1PE10.3,18X,'*')
      WRITE(NPRNT,1060)
      WRITE(NPRNT,1060)
      WRITE(NPRNT,9520)
      RETURN
      END
```